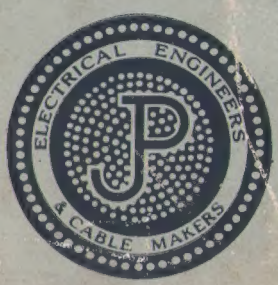
The J&P Switchgear Book



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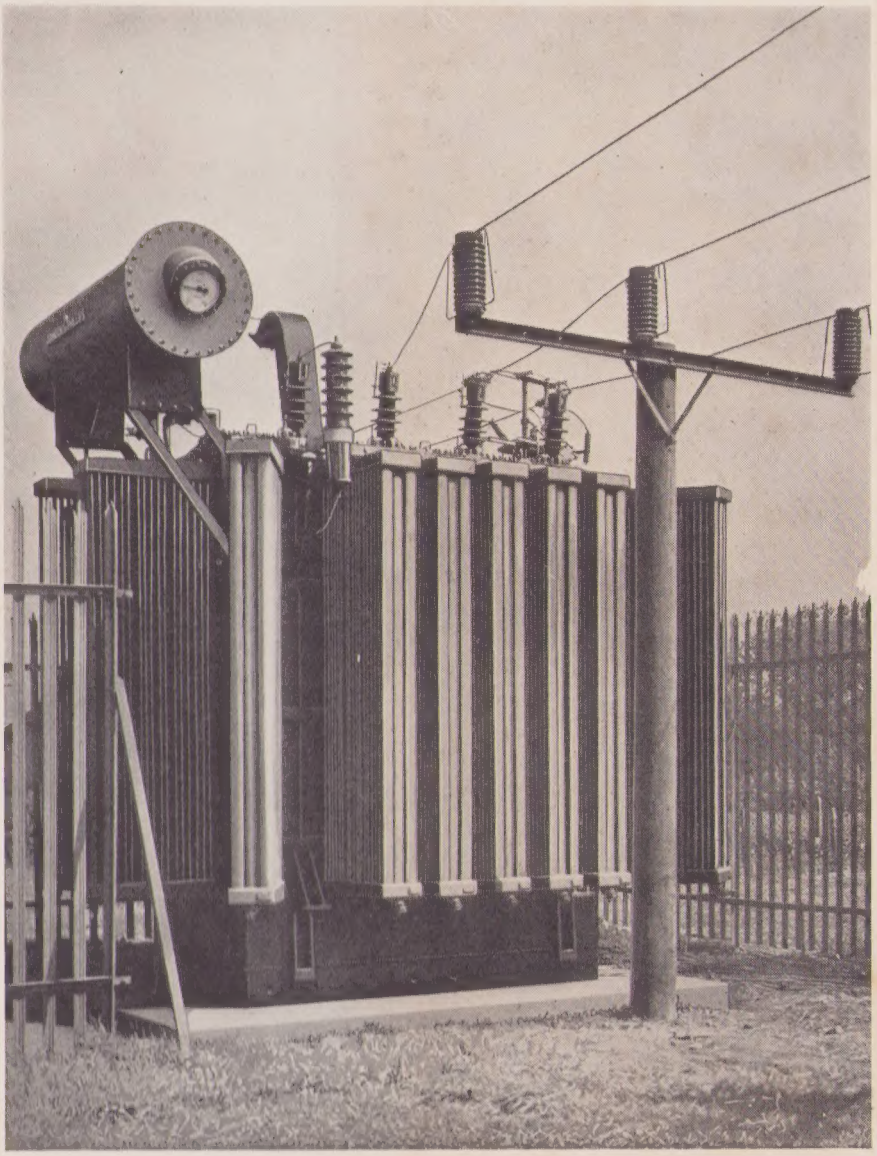

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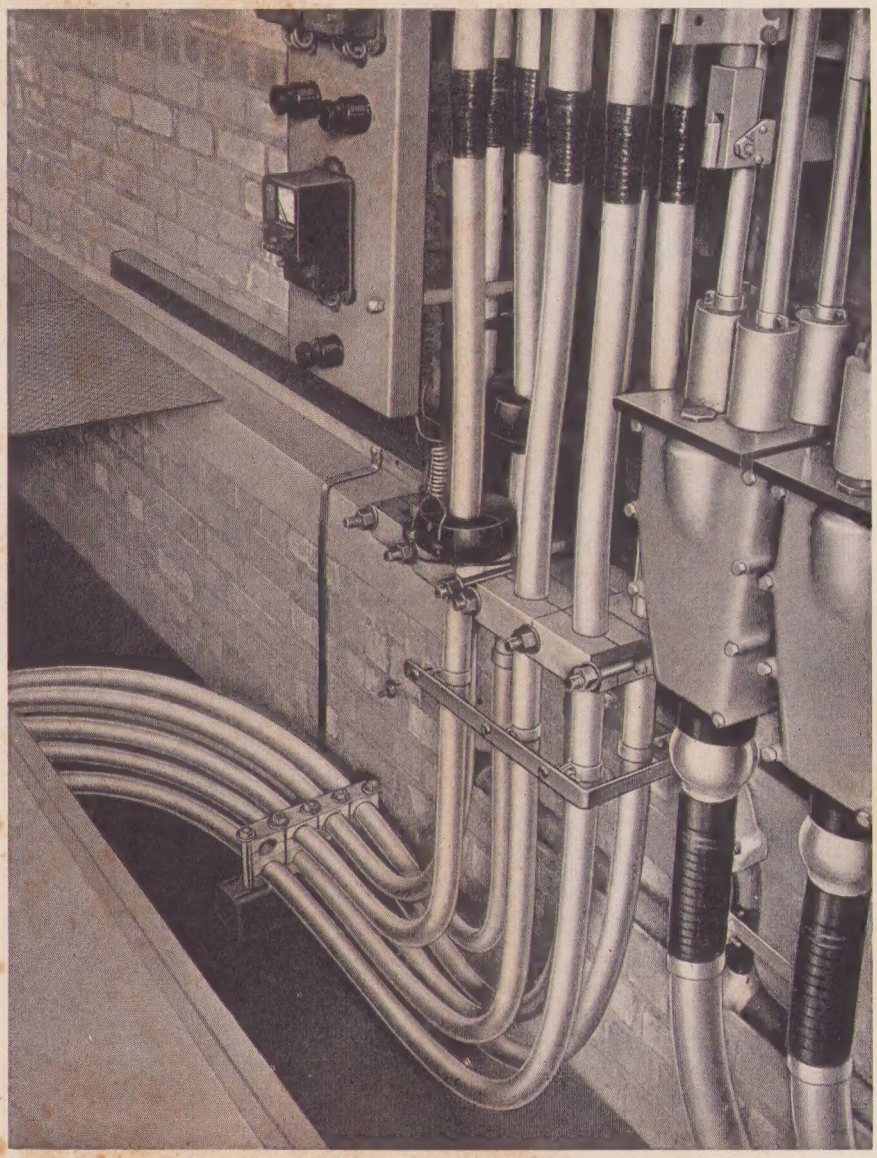

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The
J. & P. Switchgear Book

being an

Outline of Modern Switchgear Practice

for the

Non-Specialist User

by

R. T. Lythall

M.I.E.E., M.Am.I.E.E.

Fourth Edition, 1947
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PUBLISHERS' NOTE

WHEN in 1943 a second volume of the Switchgear Book was published, the author realised that the information contained therein was supplementary to the first volume, and, but for paper difficulties, a completely new edition would have been prepared. This intention is now fulfilled, and the present, fourth, edition supersedes both the previous volumes.

The increasing flow of requests for copies of the J. & P. Switchgear Book proves how much overdue is this new edition. Difficulties of book production and the many other demands on the author's time have prevented us republishing earlier.

Although much new information is included, we trust it does not overstep the bounds of its original purpose: a handbook for the non-specialist user. It is published with the hope that it will prove of service to all those concerned with the selection, operation and maintenance of switchgear.

JOHNSON & PHILLIPS, LTD.

PREFACE

THE useful nature of this work has been proved by the constant demand for copies. When the first issue of the present series appeared in 1938, followed by a reprint in 1939, it was appreciated that much material had been omitted and when, in 1942/3, an opportunity occurred to remedy this position, the need for economy in paper led to a decision to publish the additional material as a second volume rather than to re-issue as a whole.

This led to an untidy mixture where material in the second volume was additional to that in the first. The conclusion of hostilities, coupled with the need for reprinting or re-issue, has provided the opportunity to re-write the book, combining and adding material with an improved layout.

In general, the original theme has been retained, *i.e.*, that of providing an outline of switchgear practice for the non-specialist user and for students. As previously, no attempt has been made to make the book a mere catalogue of the practice of one maker. It contains many references to the practice and designs of numerous manufacturers to whom the Author expresses acknowledgment here as a whole and by name elsewhere.

There is much that is new in the present issue. In particular, the trend towards air-blast switchgear has influenced the Author to include a chapter on this subject, a chapter which gives prominence to British designs and development as an offset to the much publicised Continental and American productions.

The information put at the Author's disposal by colleague manufacturers is very valuable and appears for the first time in a book of this type. A particular debt is owing to these firms.

Acknowledgment is due to The Institution of Electrical Engineers for permission to utilise certain illustrations used by the Author in a paper presented to the Institution, and to Sir Isaac Pitman and Sons, Ltd., for permission to use two examples from the book "Calculation of Fault Currents" published by them.

The Author also acknowledges the assistance of many of his colleagues in the preparation of the book. The new chapter on Supervisory Control has been contributed by Messrs. L. H. Berridge and J. T. Ludlam; Chapter XXI, which appeared as an Appendix in earlier issues, was contributed by Mr. W. A. Brown, late of Messrs. Johnson and Phillips, Ltd., and now Engineer to Northmet No. 2 Sub-Area, Eastern Electricity Board. Mr. S. Austen Stigant gave valuable assistance with Chapter XXII, as also did Mr. W. A. Brown with Chapter XVIII.

The new chapter on flameproof switchgear has been based on material contributed by The Belmos Company, Ltd., while suggestions for improvement and additions to Chapter XXVIII made by Mr. H. W. Swann have been particularly valuable.

The Author acknowledges, too, the encouragement accorded to him by Messrs. Johnson and Phillips, Ltd., on whose initiative the work has been undertaken and produced.

Egham, 1946. R. T. LYTHALL.

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CHAPTER 1

INTRODUCTION

Of the many branches of electrical engineering, few can compare in complexity of detail, or contain so many items of apparatus (each complete in itself), or take on such a variety of form, layout or make-up, as switchgear; and yet achieve the same object, namely the efficient and safe control of electrical power. Of types, and variations of types, there seems no end, and with the advances made in the art during the past decade these have multiplied considerably. For these reasons no one book on the subject can pretend to be complete and cover every known arrangement or feature.

Switchgear, at one time regarded as a necessary evil, is now acknowledged as a separate science, demanding engineers highly trained in the art of design and application with, albeit, more than a fair knowledge of the plant they wish to control. It is a science which moves rapidly ahead, introducing new and better means of control almost before the previous advance has been absorbed. Switchgear has a range which can only be described as enormous. It enters into every electrical application, from the humblest and smallest of works to the high power supply system such as that of the Central Electricity Board. Each has a different requirement but certain fundamental principles apply to all. The supply to the humble works must be protected, though not so elaborately, as must the C.E.B. network. It is the application of switchgear, and all that goes with it, to this range of demand that makes it complex.

Of types, claims abound concerning the advantages of one against another. In this book, where advantages exist they will be noted, but no attempt will be made to influence the use of any type, because so much depends on circumstances and on personal preferences. For example, the claims as between compound filled gear and air insulated have been made time and time again. Both have distinct advantages ; both have adherents ; there are situations where one is the better and the other not so good, and vice versa, but often the user is determined on one or the other purely on personal grounds.

Gone are the days when breaking capacity (or as it was then called—rupturing capacity) was a thing of mystery, being met, when it did crop up, by an intelligent guess. And while breaking capacity was something which occasionally had to be seriously considered, making capacity, on which the safety of an operator depended, was rarely mentioned. It is true that occasionally a user would require remote control, either hand or electrical, but when the latter, the reason might well be that the circuit-breaker was too large to be conveniently closed by hand. Nowadays, in all countries of electrical importance, short-circuit testing plants are the rule and short-circuit testing the only criterion of ability. The result is that the user appreciates the problems of safe control, the importance of breaking *and making* capacity and all that this implies.

This is but one aspect and is quoted only to indicate the strides made in the past few years.

The most recent tendency is towards oil-less or oil-minimum switchgear.

This is true both for low, medium and high voltages and in later chapters consideration will be given to switchgear of both types. But why should this swing-over arise? In British designs, at any rate, the modern oil circuit-breaker is second to none, and has been proved and tried. A review of electrical troubles where British switchgear has been used would not produce any overwhelming evidence that the oil circuit-breaker was the immediate cause.

The demand for oil reduction, or elimination, often arises following a breakdown where ignition of oil from the breaker has added to the effects of the breakdown. It will be admitted that oil, as an arc quenching and insulating medium, is superior to any other known medium. It is automatic in action and demands no external source of aid. Nevertheless, a demand for oil-less or oil-minimum switchgear must be respected, and it is important here to claim that because British designers have perfected the oil circuit-breaker to a degree higher than in most other countries, it does not mean that they have been behind Continental and American designers in other respects, as many designs exist, both air-blast and oil-minimum. Quite apart from any fire hazard, oil-less or oil-minimum circuit-breakers have other advantages, particularly at the higher voltages and breaking capacities. Chief among these is that of size and in Chapter IX a comparison of the 132 kV impulse circuit-breaker with that of the earlier designs will indicate the value of this statement, the one requiring 250 gallons of oil, the other over 1,000 gallons per phase. On the other hand, air-blast gear, involving no oil whatever, demands a supply of air at high pressure, in ample quantity, and thoroughly dry. Failure of the source of air may make the gear useless from an interrupting point of view. The solution appears to be duplicate sources of air supply, a luxury for the smaller substations.

As with major issues, so with those of less importance. For example, the merits of the form of isolation in metalclad gear—vertical or horizontal—may be argued indefinitely. Will a switch-fuse suffice or must it be a circuit-breaker? There are those who consider a 4-inch instrument is ample on any control board while others insist on the large 8-inch instrument to be read at 20 feet!

The foregoing will indicate a few of the divergent possibilities. The user makes his choice and pays accordingly. He chooses cubicles (interlocked or non-interlocked), trucks, flat-back, metalclad (air or compound filled), isolation or no isolation, oil-break or air-break, switch-fuses or fuse-switches, and so on, to his personal preference.

The chapters which follow endeavour to discuss these types, the pros and cons without bias in favour of any, except where technical considerations rule out any one type. Factors which determine the choice of ratings, *e.g.*, short-circuit, are considered in detail. Even so, the book does not pretend to be a complete guide to the art—merely an outline.

BIBLIOGRAPHY

"STANDARDISATION OF SWITCHGEAR," D. E. Lambert, B.Sc. (Eng.) and J. Christie, "Journal I.E.E.," Vol. 95, Part 1, No. 91, July 1948.

CHAPTER II

SYSTEMS OF BUSBAR CONNECTION

THE form of busbar layout selected for any particular application must depend on the flexibility of operation required and the price the user is prepared to pay for this and immunity from interruption of supply. It is generally impracticable to apply the methods adopted for a generating station to a small substation. A shut-down in the former may involve a considerable number of consumers, whereas the latter, if shut down, only causes dislocation over a relatively small area and to considerably fewer consumers. Although cost generally dominates the considerations for small substations, it is important that facilities for maintenance be kept in mind.

The number of basic arrangements of main connections is relatively few, but there are many combinations of these which are found useful in certain circumstances.

SINGLE BUSBAR.

The simplest of all busbar connections is that where a single set of busbars extend the length of the switchboard without break, and to which all generator, feeder and transformer circuits are connected. This method is general for d.c. switchboards, and is one usually chosen for the smaller a.c. substation or generating station.

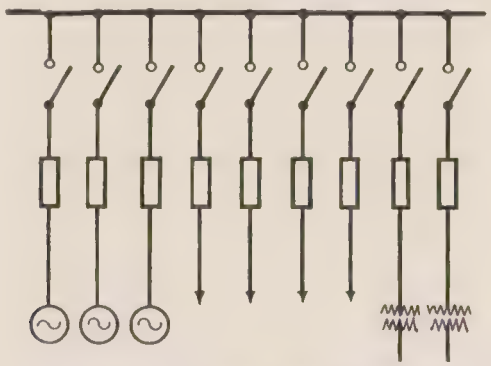


FIG. 2-1.—*Single Busbar System.*

The single busbar scheme is shown in Fig. 2-1. It is to be noted that if at any time a busbar fault occurs, all feeders will be deprived of supply. Busbar cleaning and maintenance will involve a complete shut-down. In compound-filled types of switchgear, busbar faults and the need for cleaning should not arise, so that for this type, single busbars are often more suitable. A further point not to be overlooked is that under fault conditions the combined plant of the station feeds into the fault and this may place some

limitation on the size of station which can use continuous busbars; *i.e.*, without sectionalising. In Fig. 2-1, means of isolating the circuit-breaker are indicated only on the busbar side. If, on feeders or transformers, there exists any possibility of a feed back, double isolation must be used. This point should be particularly watched in transformer circuits where they may be paralleled on the l.v. side for distribution -such paralleling may arise through an indirect route and not necessarily at a common point such as the l.v. switchboard.

Sectionalised Single Busbar.

The simple act of sectionalising the busbar results in many advantages. Chief among these is the facility it provides in operating the system in that one (or more) sections can be completely shut down for maintenance or repair without interfering with supply from other sections. The number of sections will largely depend on the importance of the station or on the limitation of short-circuit value desired. This latter is a second advantage of sectionalising in that circuit-breakers of lower breaking capacity are often possible by running normally with sections electrically segregated. If feeders to any one point are duplicated, it is usual to connect these to different sections. If sectionalising has been adopted in order to obtain a reduction in fault value, care must be taken not to parallel feeders off different sections of the main switchboard at the remote point, *i.e.*, sectionalising may be necessary at the remote point also. In general, the sectionalising switch should be a circuit-breaker so that the sections may be uncoupled even if a load transfer happens to be being made. An air-break isolator, so often used for sectionalising, is not suitable for this purpose, and if used, should be suitably interlocked so that it can only be opened or closed under no-load conditions. Air-break isolators should preferably be confined to l.v. systems.

Where a circuit-breaker is used, it should have double isolation, in order that the circuit-breaker may be completely isolated from adjacent

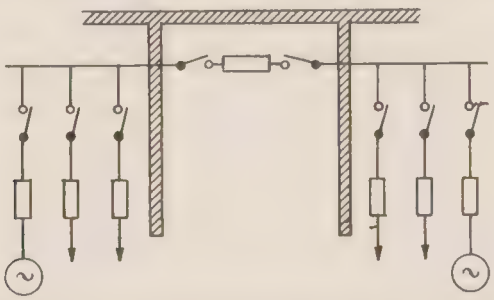


Fig. 2-2.—*Sectionalised Single Busbar System*

sections. A simple sectionalised single busbar scheme is shown in Fig. 2-2, which also indicates how fire risks may be reduced by housing the sectionalising circuit-breaker within fireproof walls. It will be appreciated that the sections must be synchronised before the section switch is closed.

Ring Busbars.

From the sectionalised scheme, the next step to give greater flexibility is to join the ends of a multi-sectionalised busbar, to form a ring, as shown

in Fig. 2-3. By this means, generating plant on any section can be utilised to supply the feeders on any adjacent section.

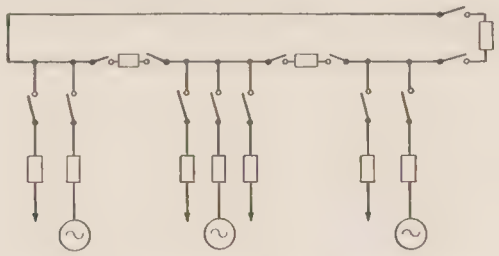


FIG. 2-3.—*Sectionalised Ring Busbar System.*

DUPLICATE BUSBARS.

In the more important stations, the use of duplicate busbars is almost universal. The advantages of the scheme from an operating and maintenance point of view more than outweigh the additional cost. Usually, one set of bars are designated "main" and the other "reserve" or "hospital." This infers that normally the "main" bars are in use with the other set available in the event of trouble. Apart from cleaning and maintenance, the existence of a second set of bars is of considerable value when, for some reason, a particular circuit demands special treatment, such as testing out a new feeder, or the running of an existing feeder at a higher voltage than normal to compensate for an abnormal voltage drop. Similarly, it is possible to carry out commissioning tests on new plant on the reserve busbars without interfering with normal services on the main bars.

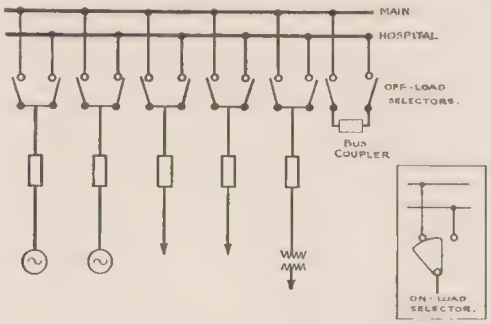


FIG. 2-4.—*Duplicate Busbar System.*

Duplicate busbars involve the use of selector switches at the switchgear. In cubicle gear, these take the form of ordinary isolating switches. In metalclad gear, removable plugs are often supplied, these being moved by hand to one position or another. Alternatively, oil-immersed selectors are used—one type being an "off-load" arrangement where a single blade, hinged at one end, is moved by means of an external handle to one or other set of contacts connected to the main or reserve busbars. In another form, the blade is in the shape of a fan and makes contact with one set of contacts before breaking on the other, and is an "on-load" type.

The two sets of busbars must be paralleled before operating the selector switches, and this is done through a busbar coupler switch, as shown in Fig. 2-4.

This switch may or may not have automatic features, but in any case should be interlocked with the selector switches. This is usually accomplished by means of keys, suitably trapped until the busbar coupler is closed. This interlock can be combined with a synchronising scheme.

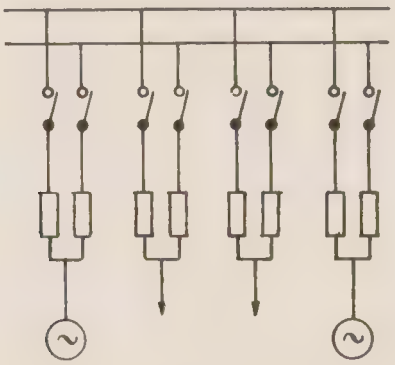


FIG. 2-5.

In an alternative form of duplicate busbar scheme, duplicate circuit-breakers are used for each circuit. This scheme does not require a busbar coupler switch, but it is costly and is generally only used in major stations. It is a scheme which gives greatest facility for circuit-breaker maintenance. The layout is shown in Fig. 2-5.

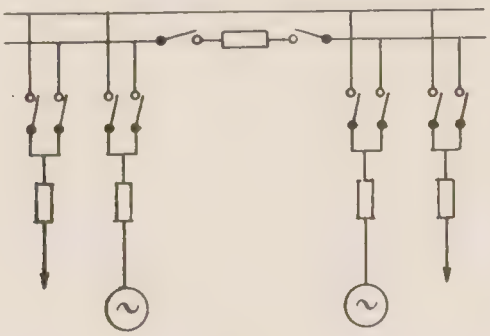


FIG. 2-6.

SECTIONALISED DUPLICATE BUSBARS.

This scheme is shown in Fig. 2-6 and provides very considerable flexibility. Any section of busbar can be isolated for maintenance while any section can be paralleled with any other through the reserve busbars. Normally, sectionalising of the reserve bars is unnecessary, although this can be done if required. Busbar coupler switches can be provided on each section.

Duplicate Busbars with By-Pass Isolators.

Instead of using duplicate circuit-breakers, a scheme may be used in which a by-pass isolator is incorporated as shown in Fig. 2-7. It is only suitable for cubicle type switchgear and the isolating switch is generally connected to the reserve busbars. If it is required to take a circuit-breaker out of service, the circuit may be kept in service by closing the by-pass

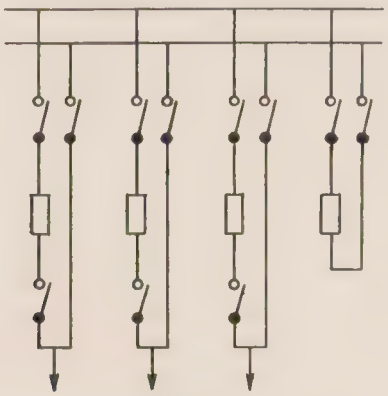


Fig. 2-7.

isolator after the breaker circuit has been cleared both at the breaker and its isolating switches, and then closing the busbar coupler. As the circuit still demands protection, this is usually provided at the busbar coupler, by means of back-up overcurrent protection.

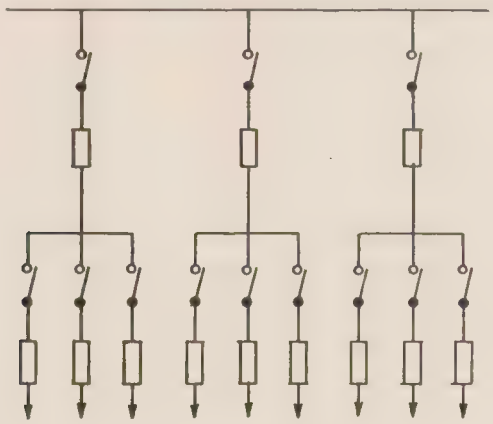


Fig. 2-8.

Group Switching.

It often happens that when the station capacity increases, existing switchgear will have insufficient breaking capacity. If there are a considerable number of feeder circuits, it becomes a costly item to replace the circuit-breakers by new, and a group switching scheme is often resorted to. This scheme is shown in Fig. 2-8, where groups of feeders are connected to the

generators through circuit-breakers of ample breaking capacity. It will be clear that if a fault occurs on any of the feeders, the group circuit-breaker must open to clear it. This is a disadvantage in that all feeders connected to that group circuit-breaker are out of service until the faulty circuit is cleared. In order to ensure the opening of the group circuit-breaker, a scheme of interlocking is necessary, usually accomplished through relays. This scheme will permit a feeder circuit-breaker to clear an overload within the capacity of that circuit-breaker.

Before adopting the group switching scheme, it is essential to check that the feeder circuit-breakers can carry the maximum fault current until cleared on the group circuit-breaker. It must also be remembered that a feeder circuit-breaker may be closed on to a fault, a duty for which it may not be suitable.

A modification of the scheme, and one to be recommended, includes reactors between the group feeder and the secondary busbars, as shown in Fig. 2-9.

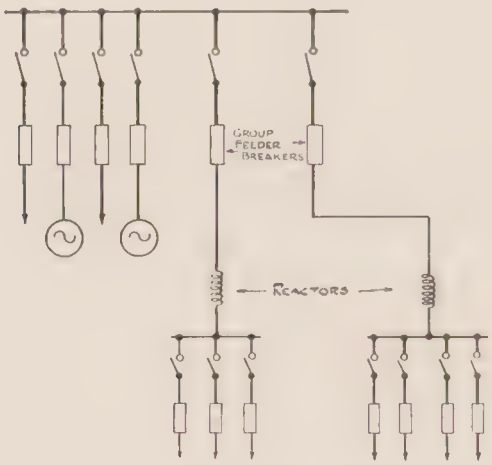


FIG. 2-9.—*Group Switching System.*

TRANSFORMER SWITCHING.

In networks where transformers are employed to step up to a suitable transmission voltage, a variety of switching schemes are available. These are shown in Figs. 2-10, 2-11, 2-12 and 2-13.

The scheme which allows for switching the transformer and line as a unit is adopted to economise in switchgear, as none is required on the h.v. side. It has the obvious disadvantage that a transformer breakdown involves also the loss of the line. The practice of treating a generator and transformer as a unit has the same disadvantage as trouble with one involves the other. It has the advantage that heavy current switchgear at relatively low voltage is not required. The two can be adequately protected as a unit, and magnetising current rush on switching-in is eliminated.

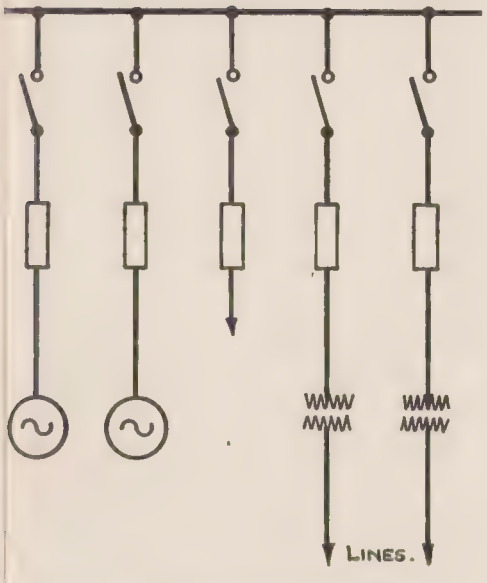


FIG. 2-10.—*Transformer and Line switched as unit.*

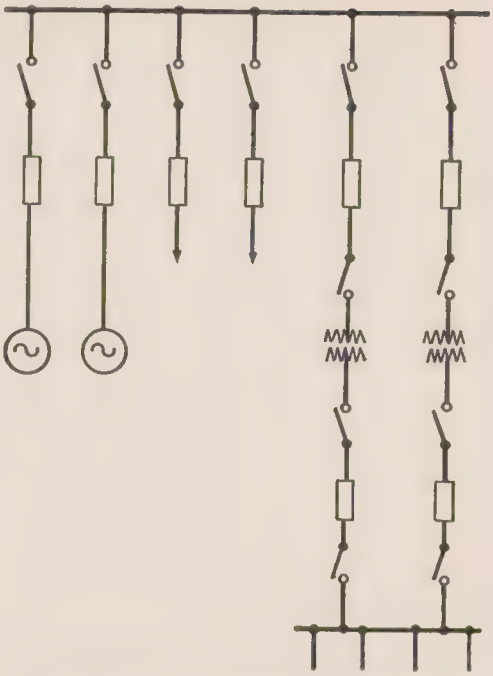


FIG. 2-11.—*Independent Switching of Transformers.*

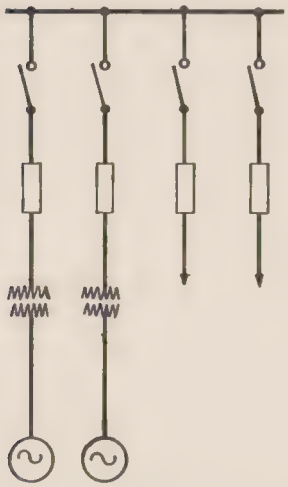


FIG. 2-12.—*Generator and Transformer switched as unit.*

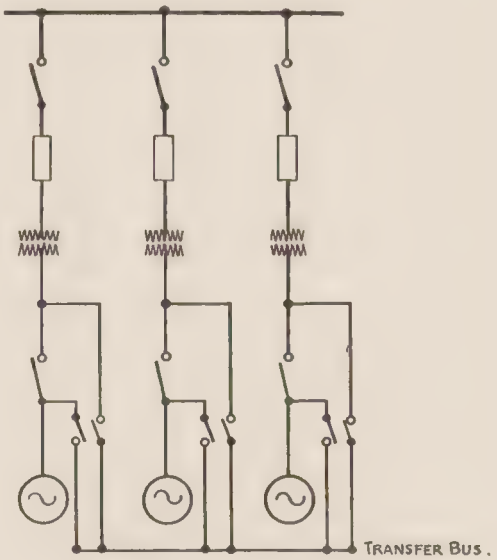


FIG. 2-13.—*Transfer Busbar System.*

An alternative to the foregoing is a scheme using a transfer busbar. This is used on the Continent and is only suitable for cubicle type switchgear. This scheme allows the connection of any one generator to any transformer via the transfer busbar. All the schemes for transformer switching, though shown for single busbars, can be elaborated by the use of duplicate busbars, sectionalising, etc.

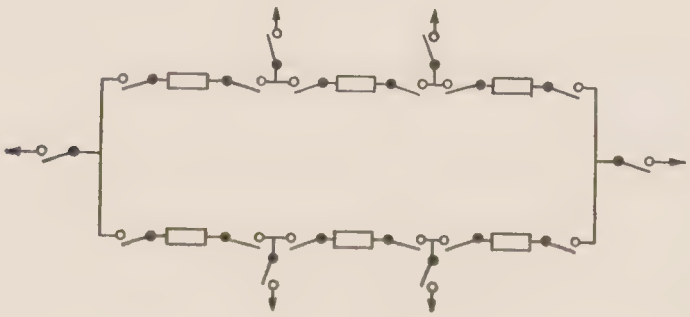


FIG. 2-14.

MESH SCHEME.

A scheme which has been adopted in major stations is known as the mesh scheme, shown in Fig. 2-14. It is a development of the three-switch scheme adopted on the British Grid network, for schemes where there are more than two feeders. It economises in the use of circuit breakers (by comparison with a duplicate busbar scheme) but the total number of

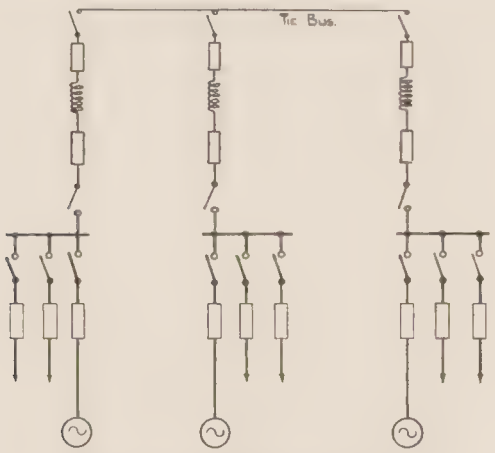


FIG. 2-15.—*Reactors in Tie Bars.*

circuit-breakers is the same as the number of circuits. The saving is in the elimination of the busbar coupler. To make any circuit dead, two circuit-breakers must be opened, *i.e.*, the two adjacent to the circuit in question. Protection must include for the tripping of two circuit-breakers and therefore complicates the scheme.

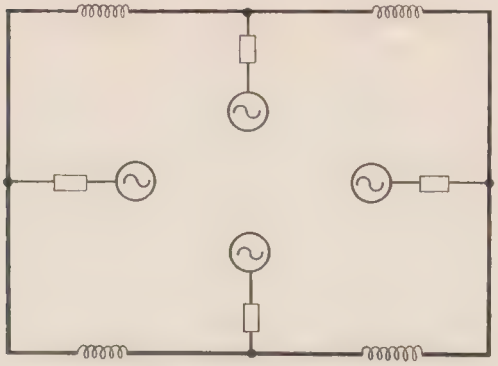


FIG. 2-16.—*Reactors in Ring Busbars.*

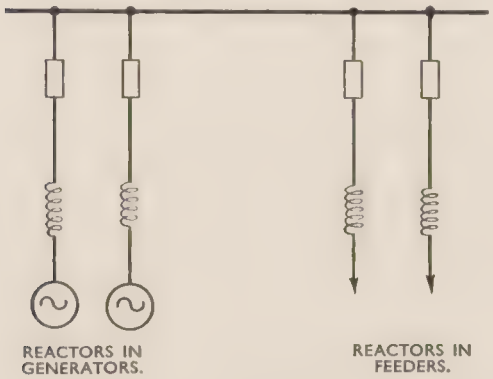


FIG. 2-17.—*Reactors in Generator and Feeder Circuits.*

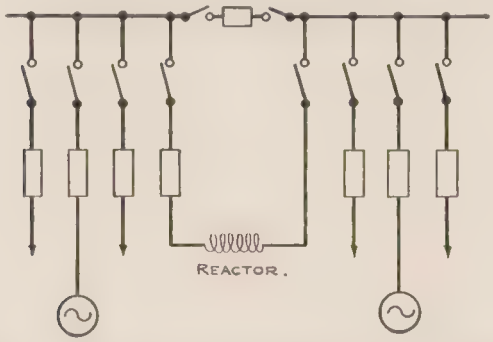


FIG. 2-18.—*Short-circuiting scheme for Reactors.*

REACTOR SCHEMES.

Many of the schemes so far considered can have generator, feeder or busbar reactors included in order to reduce the value of fault current to a safe figure. Details of the use of reactors are given in Chapter XXIV. Typical diagrams are given in Figs. 2-15, 2-16, 2-17 and 2-18.

CHAPTER III

DIRECT CURRENT SWITCHBOARDS

In spite of the general tendency for all but the simplest and cheapest forms of a.c. switchboards to be of a cubicle or metal enclosed type, the practice of flat-back panels, generally of slate or of ebony Sindanyo (an asbestos-base synthetic phenol product) remains good practice for d.c. Whereas in a.c. practice the dead front is demanded, even at the lowest voltages, in d.c. much apparatus is mounted on the front of the panel, mainly comprising the air circuit-breakers and knife switches.

A typical switchboard for a traction substation is shown in Fig. 3-1. It is for such applications that the majority of d.c. switchboards are supplied to-day.

Fig. 3-1.—*Typical d.c. Switchboard for Traction Substation.*

The flat-back switchboard is mounted at about seven feet from a wall, providing a passage way at the back with a specified clearance between the wall and live connections. This clearance is specified in B.S.194. Access to the rear of the board must be restricted. This is accomplished by means of expanded metal end screens and lock-up doors at both ends of the board.

The metal structure of the flat-back switchboard comprises a framework of angle or channel irons bolted together, or in later designs, a tubular construction with grip fittings. This type, more costly in fittings, eliminates much drilling and makes adjustment of any cross members from the upright

members easy. The type is well known in the building industry for scaffolding.

Unless the structure is all welded, the complete framework must be substantially bonded together and earthed.

Busbar and connection supports may be of the simplest form. Typical of these are a channel form of insulating material, probably Sindanyo, or bakelite board. Alternatively, the simplest type of pin type insulator may be used, with a stirrup fitting carrying the busbars and turned to clamp on to them.

The circuit-breaker used is usually of the air-break type. Two forms are shown in Fig. 3-2 and 3-3, the former having carbon breaks, the latter having magnetic blow-out, with the break taking place between metallic contacts.

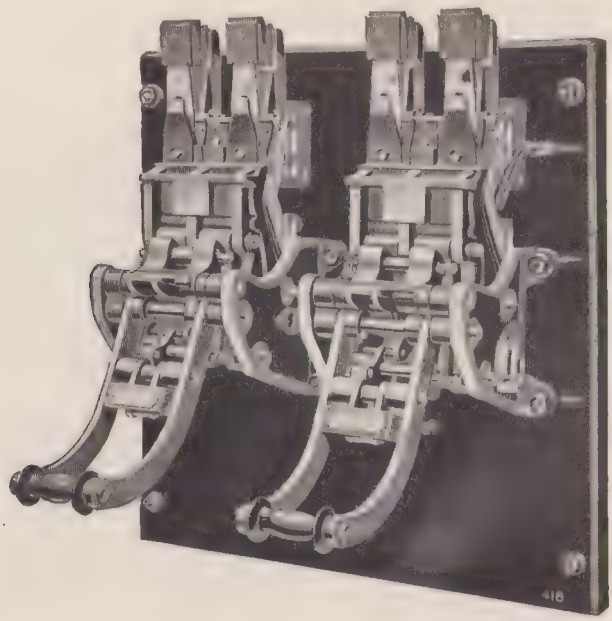


FIG. 3-2.—*Air-Break Circuit-Breaker, 3,500 ampere rating, of the carbon break type (Whipp & Bourne, Ltd.).*

In the carbon-break type, a laminated brush carries the main current while arcing contacts are provided on which the arc is finally broken. Carbon is employed as it does not readily volatilise and is less dangerous therefore to an operator standing close up to a circuit-breaker. The arc is broken by being extended to a length where it becomes unstable and cannot be maintained by the available voltage, noting that the voltage drop in the arc is roughly proportional to its length. Extinction is further assisted by the natural tendency of the arc (regarded as a flexible conductor) to embrace as large a field as possible. The tendency to " balloon " upwards indicates

the advisability to mount an air circuit-breaker at the top of the panel with nothing above to which the arc can spread.

In the magnetic blow-out type, the arc is drawn across a magnetic field set up by the current in the arcing circuit. No matter what direction the flow of current, the strength of the field behind the arc is increased, and weakened in front, thus forcing the arc upwards until it attains unstable length and is broken. The separation between contacts in this type can be much less than in the carbon-break type. Contact wear is less and arcing times are relatively short. The shorter arcing time may be a disadvantage

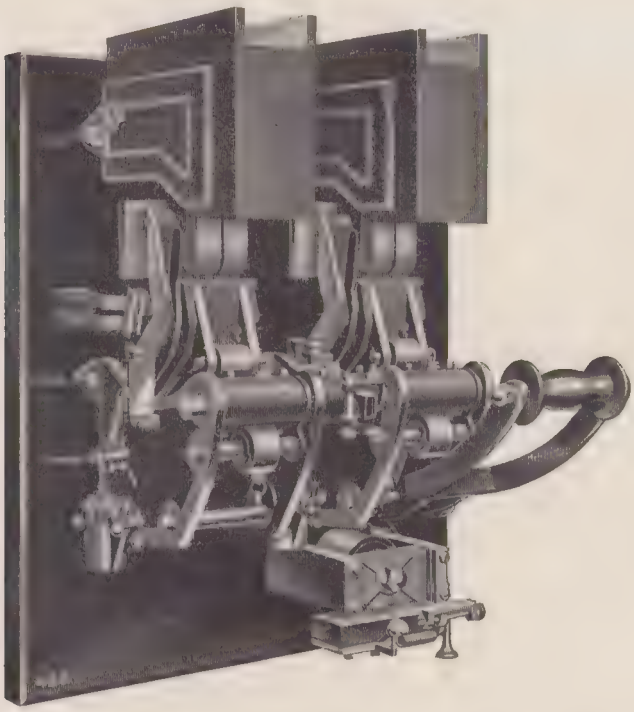


FIG. 3-3.—*Air-Break Circuit-Breaker, 1,500 ampere rating, of the magnetic blow-out type (Whipp & Bourne, Ltd.).*

on inductive circuits due to the high voltage rise caused, often three times normal voltage. This condition may require the fitting of discharge resistances switched into circuit by means of auxiliary contacts. The field varies proportionally with the current and therefore performance when breaking light currents may be erratic.

Both types of air circuit-breaker can be fitted with all the usual automatic features such as overload, low-voltage, reverse and shunt trips. In general, the tripping mechanisms are actuated by the main current without the use of relays. Overload releases have a range of 100% to 250%, and reverse

releases operate at about 10% to 15% of normal full-load current in a reverse direction. The principle of a reverse current release is indicated in Fig. 3-4. This type of release comprises a magnetic circuit, and an

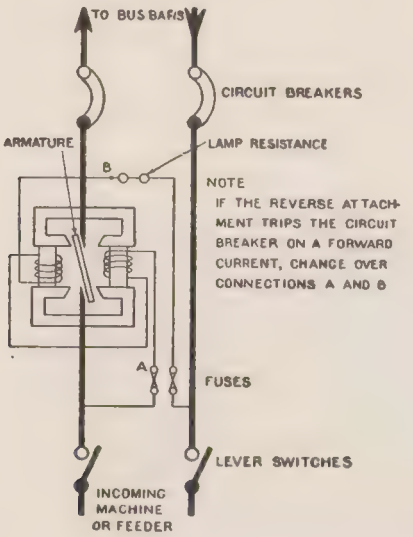


FIG. 3-4.—*Diagram to illustrate the operation of a reverse current trip on air circuit-breaker.*

armature energised from a high resistance voltage coil connected across the supply, and by one conductor carrying the main current. When current flow is in the normal direction the voltage coil and the main current energise the magnetic circuit so that the armature is held in the position for " breaker closed." On a reversal no change occurs in the voltage element but the magnetic conditions are altered due to the reversal of the main current. In this condition, the armature is rotated on its spindle to trip the circuit-breaker.

Operation of air circuit-breakers may be by hand, or d.c. solenoid, the latter being necessary on the very heavy current ratings. Single pole units may be used coupled to a common closing mechanism or alternatively each pole may be closed separately, but in this case an interlocking arrangement ensures that all units open simultaneously.

Knife switches as used on d.c. switchboards need little description. They are available in two types—slow-break and quick-break—although there is a lower upper limit of current carrying capacity for the latter. Quick-break action is obtained by snap-out auxiliary blades which open after the main blades, the action being independent of the speed of operation at the handle. While a quick-break switch can break reasonable load current, it should not be relied upon for heavy duty, this being the province of the circuit-breaker.

The majority of present-day knife switches are designed so that the hinge contact is current carrying. The prejudice against this has almost passed in view of proof that the contact resistance at the hinge is less than

that at the upper contact clip, due to the spring washers under the hinge bolt.

Practical difficulties in the way of bedding-in large contact surfaces arise by the use of multiple blades essential for the higher currents. In slow-break switches for the heaviest currents, a jaw clamping device is used so that while maximum pressures are obtained with the switch closed, reasonably light operation is achieved after slackening off the clamps. In this type, too, the jaw and hinge contact strips are taken right through the supporting panel without break or joint. This arrangement, shown in Fig. 3-5, makes for an easy junction at the back of the panel with the circuit

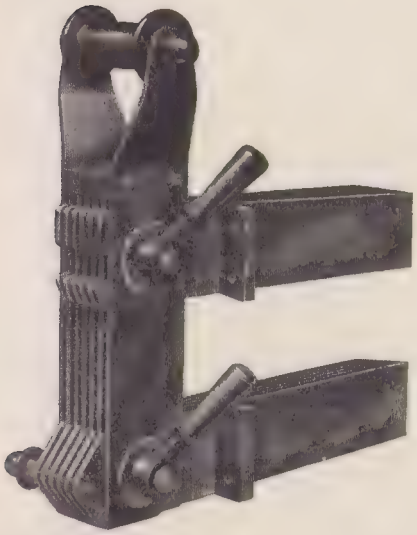


FIG. 3-5.—*Heavy Current Slow-Break Knife Switch with jaw clamping devices.*

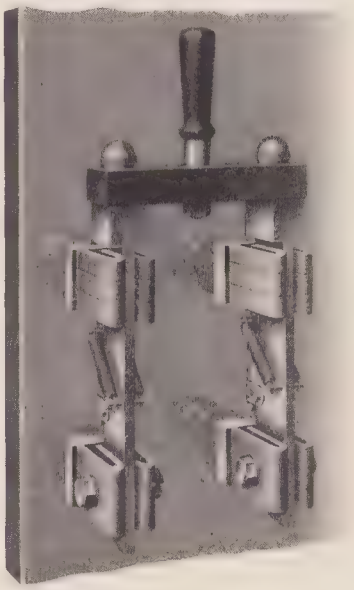


FIG. 3-6.—*Quick-Break Knife Switch.*

connections away from the switch. Fig. 3-6 shows a typical double pole quick-break knife switch.

The use of oil circuit-breakers on d.c. is very limited. In certain circumstances it may be necessary to use totally enclosed ironclad oil circuit-breakers and in this case it is very essential that regular inspection and renewal of the oil be maintained due to the fact that a d.c. arc rapidly carbonises and deteriorates switch oil. Since a d.c. arc has no current zero, the arc is interrupted suddenly and, if the circuit is inductive, dangerous pressure rises occur.

CHAPTER IV

HIGH VOLTAGE ALTERNATING CURRENT SWITCHGEAR

High voltage switchgear for use indoors usually takes one or other of the types :

(*a*) Cubicle ;
(*b*) Draw-out or Drop-down Truck ;
(*c*) Metalclad Filled ;

and, in a broad way, this is also the order of cost. The advantages and disadvantages of one or the other must be weighed up on each installation. The greatest advantage which types (*a*) and (*b*) have over (*c*) is that of accessibility to all apparatus in the individual circuit. The advantage which (*c*) has over the other two is the introduction of complete earthed metal enclosure.

(*a*) Cubicle Type Switchgear.

In this type, the cubicle may be of metal or of stone. In the former case, either bolted or welded structures may be used, and doors giving access either at back or front or both may be provided. The latter is preferable, and is recommended even though it may mean a few feet on the width of the substation. Such an arrangement allows for better maintenance as access is from two sides and a better disposition of the gear is possible within the cubicle. This is generally divided into compartments by means of horizontal barriers, and connections are taken through these by means of porcelain insulated stems. A typical switchboard of the metal cubicle type is shown in Fig. 4-1 with the end sheets removed to show the apparatus within.

This board is arranged with duplicate busbars and selection is by means of interlocked air-break isolators of the gang-operated type two operating spindles are brought to the front of the cubicle.

No feeder (cable) isolators are fitted to this board. Where these are necessary (see Chapter II) the layout becomes more difficult and this simple item makes for a larger cubicle and a complication in arrangement. In the illustration Fig. 4-1, a voltage transformer is shown connected on the cable side. It is conveniently arranged to plug-in beneath the circuit-breaker tank. This means that the voltage transformer must be withdrawn before the circuit-breaker tank can be lowered.

The danger with the simplest form of cubicle is that there are no safeguards against operation of isolators before the circuit-breaker, or against access to the internal gear under conditions of danger.

This danger can be overcome by the introduction of interlocks, either mechanical or electrical. The former are an added complication and are not easy to apply. In many cases, it is not a difficult job to defeat a mechanical interlock and if this can be done, a false sense of security is given. With electrical interlocks, a separate source of supply is essential.

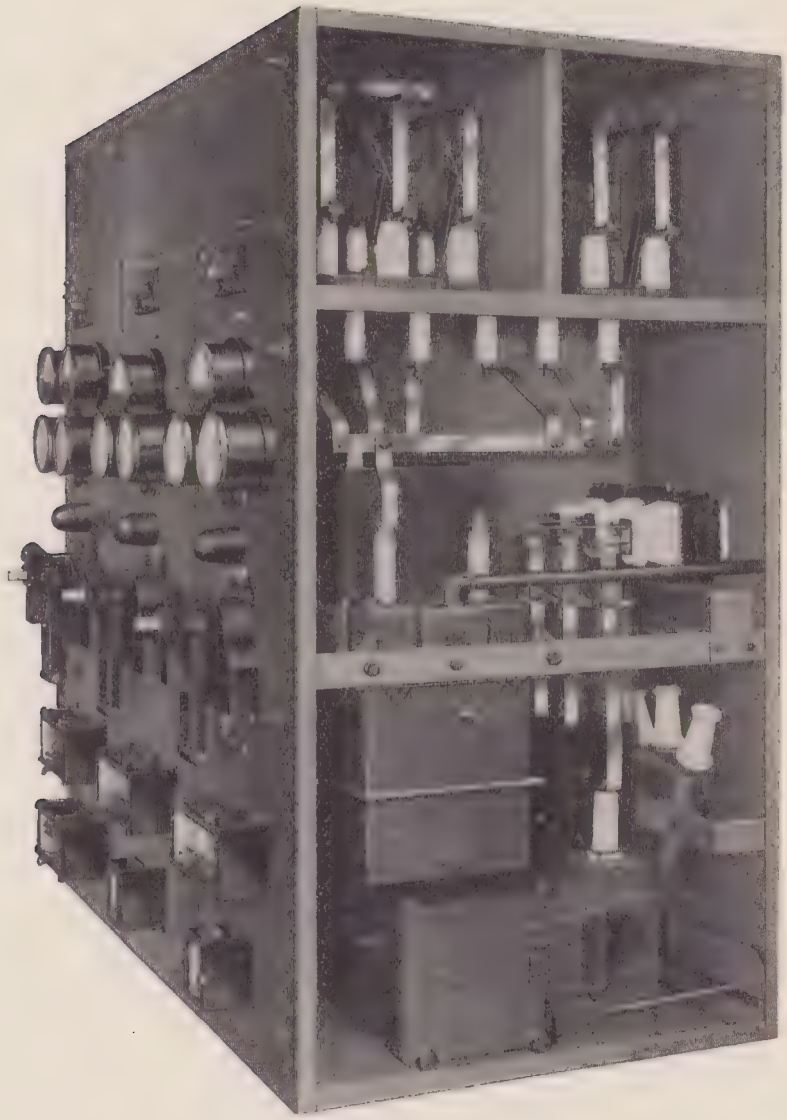


FIG. 4-1.—*h.v. Cubicle Type Switchboard with duplicate busbars and off-load selectors.*

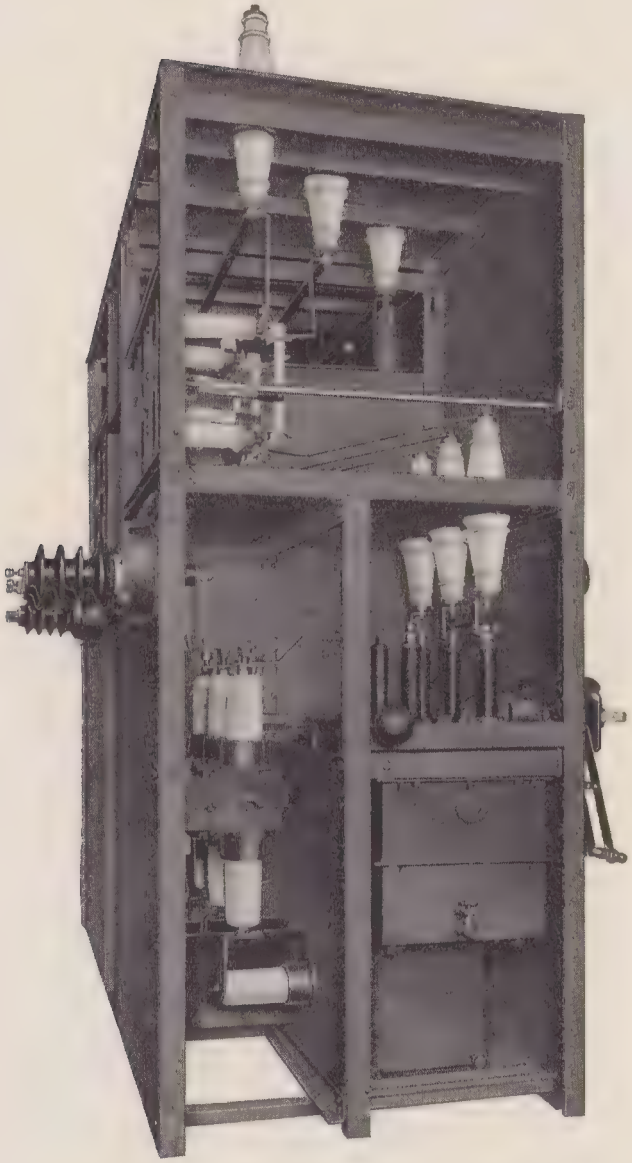


FIG. 4-2.—*22kV Cubicle Type Switchboard.*

A means of checking that this is healthy at all times should be provided, probably by a " healthy circuit " lamp.

The cubicle type of gear has limitations and in general, 33 kV should be regarded as the upper limit of voltage, while 500 MVA is the upper limit of breaking capacity. Undoubtedly, cubicles can be built for higher limits but they become completely unwieldy and, compared with

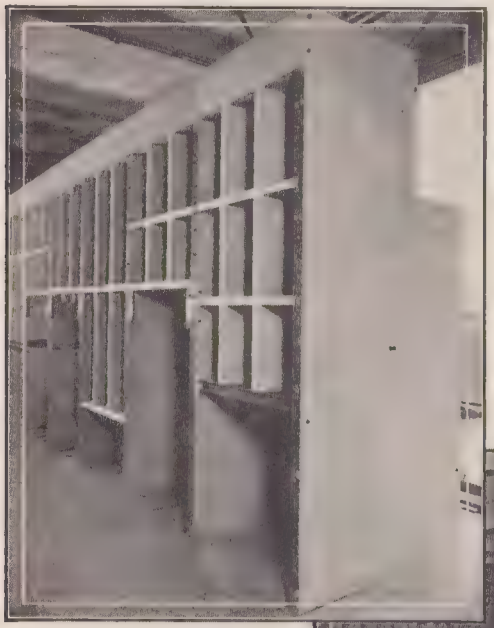


FIG. 4-3.

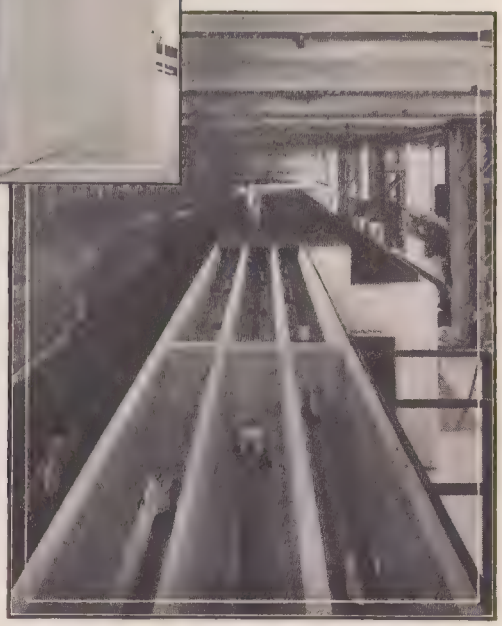


FIG. 4-4.—
Stonework Cubicles in course of erection.

other forms, notably the filled type of metalclad, demand very large buildings.

Fig. 4-2 illustrates a metal cubicle type of switchboard for 22 kV, again arranged with a plug-in voltage transformer on wheels beneath the circuit-breaker tank.

When the cubicles are built of moulded stone, it is usual to allow for phase separation throughout, the dividing walls also being in stone. The material must be regarded as being at earth potential and full clearances maintained accordingly. All metal cases, frameworks, etc., must be

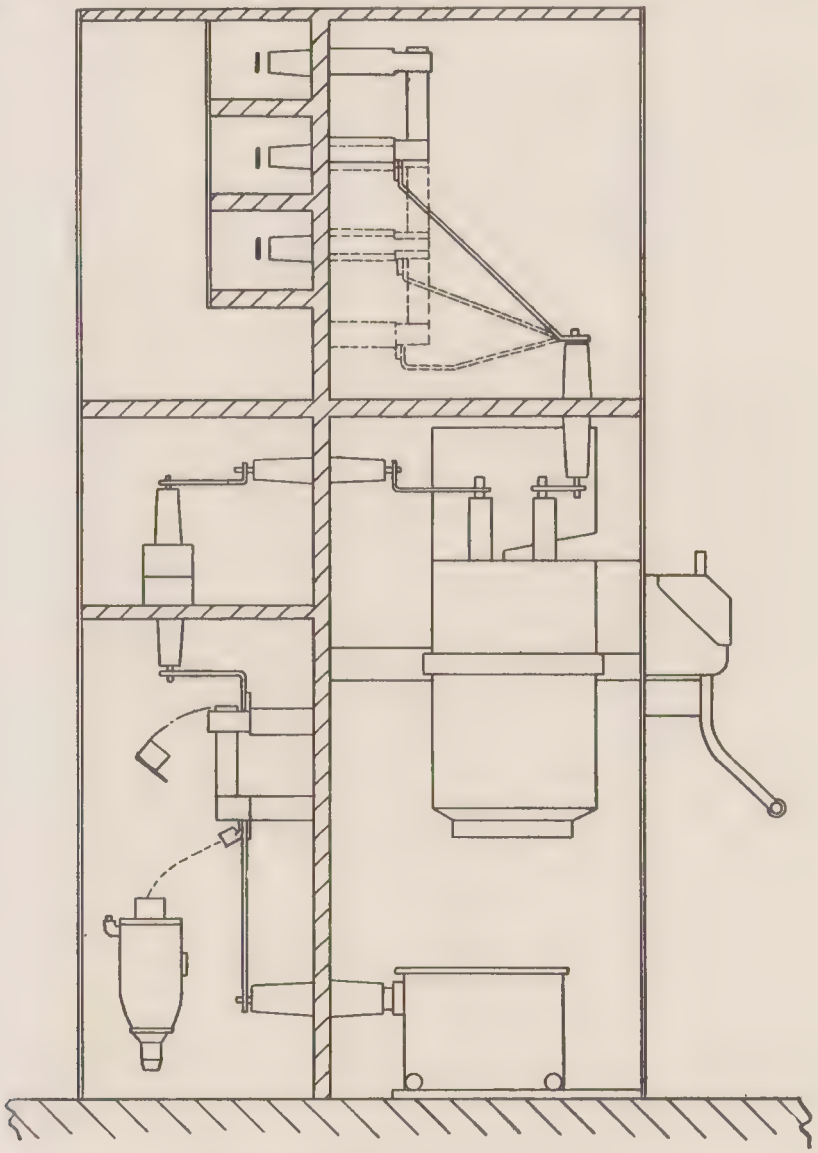


FIG. 4-5.—*Stonework Cell, Single Busbar.*

properly connected to the earth bar. Figs. 4-3 and 4-4 will serve to illustrate typical moulded stone cubicles in course of erection.

It is usual for the slabs forming the structure to be pre-cast, all holes

necessary for the support or fixing of the apparatus being cored in the slab.

Considerable accuracy is necessary in this method, and this has been achieved by several firms specialising in this class of work. The concrete

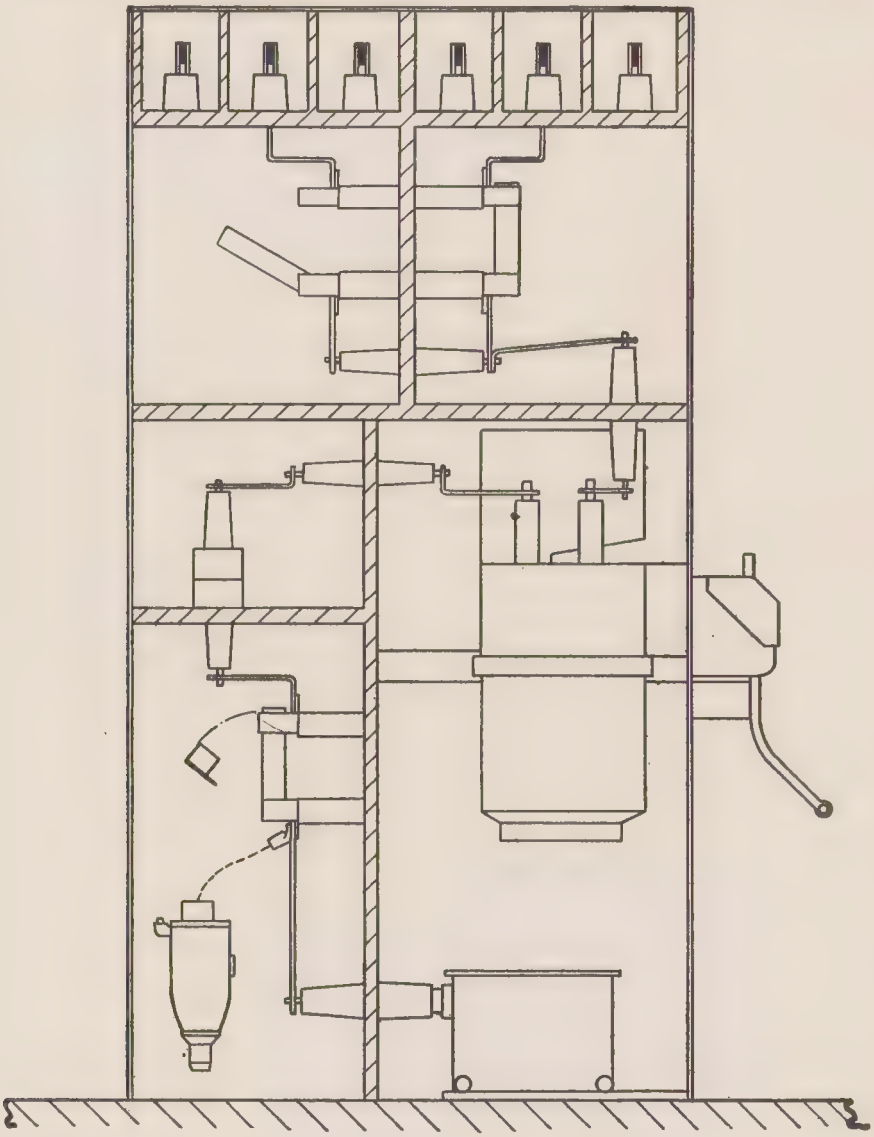


FIG. 4-6.—*Stonework Cell, Double Busbar.*

mixture should be strong enough without reinforcement and comply with B.S.268 (Switchgear Cells and Cubicles constructed of Concrete or Moulded Stone).

The arrangement of the gear within the cubicle follows generally that adopted in sheet metal cubicles except that, in order to maintain phase separation throughout, single-pole, pole-operated isolators are used instead of triple-pole gang-operated.

Figs. 4-5 and 4-6 are typical cross-section arrangements of moulded stone cubicle switchgear.

The moulded stone type of cubicle is more suitable for the higher range of gear previously mentioned, *i.e.*, 33 kV and 500 MVA, and, if more than one floor is acceptable, it may be possible to use this type up to 66 kV.

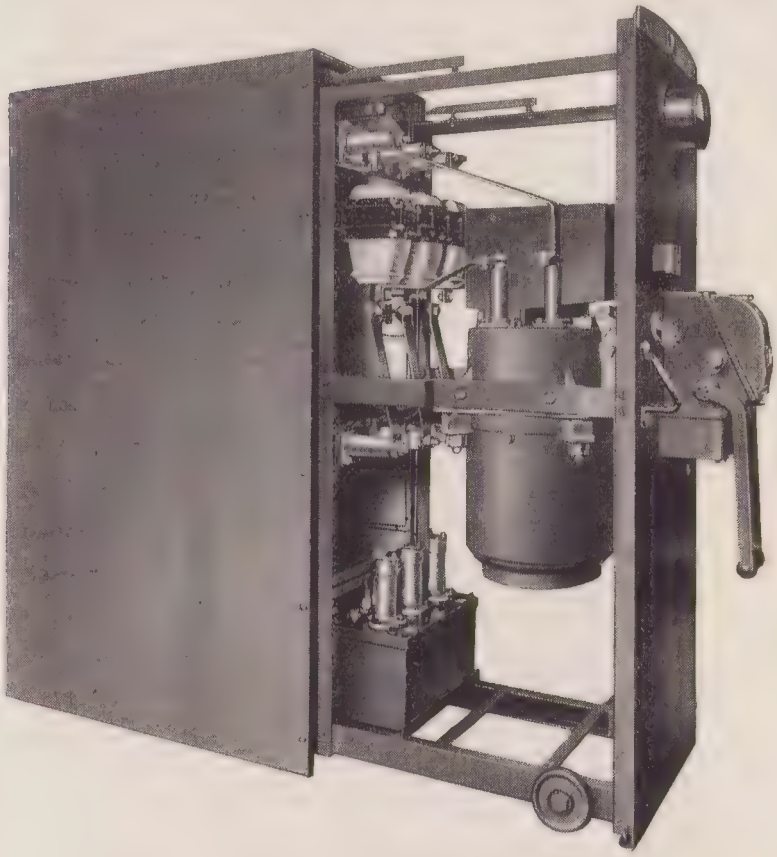


FIG. 4-7—*Draw-out Truck Type Metalclad Cubicle.*

(*b*) DRAW-OUT OR DROP-DOWN TRUCK TYPE.

From the metal cubicle type of gear, it is not a big step to the truck type, in which the major part of the equipment is carried on a movable carriage. The first trucks were built as long as 35 years ago, and for many situations they form an excellent choice. In the draw-out type, particularly, access to apparatus within the truck is very easy. This may be judged by a study of Fig. 4-7 where the moving carriage is in a partly withdrawn position. In the fully withdrawn position it will be clear that the circuit-breaker, the isolating contacts, the current transformer, and all connections

between them, are accessible from the back and the two sides. Suitable interlocks ensure that the truck cannot be withdrawn unless the circuit-breaker has been tripped open. When withdrawn, suitable shutters automatically cover the live isolator contacts on the stationary position. Provision is made for locking these shutters.

Withdrawal of the truck completely isolates the circuit-breaker and, if required, a voltage transformer is carried on the base of the structure and is automatically withdrawn with the truck. An example of this is shown in Fig. 4-8. Secondary connections, both current and voltage, are made through suitable plug connectors and are isolated on the withdrawal of the truck.

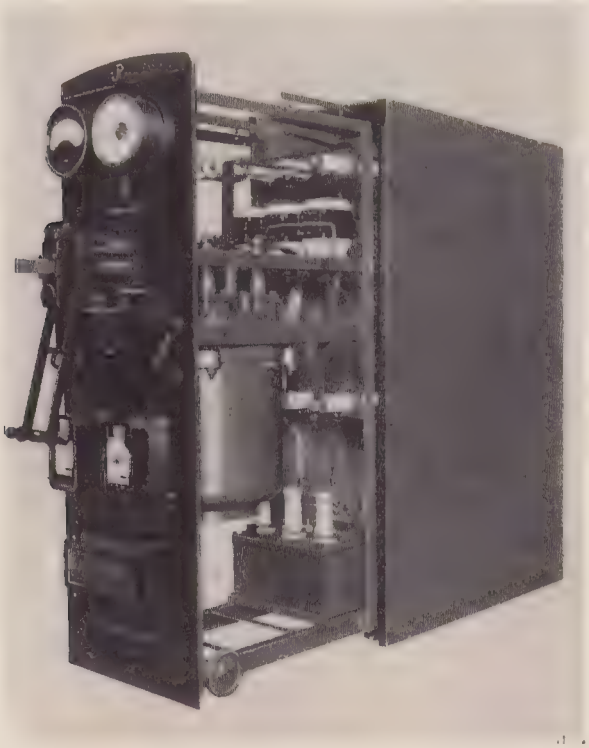


FIG. 4-8.—*Truck Type Cubicle, 250 MVA breaking capacity.*

Under short-circuit, the passage of the current tends to force the truck out and it is necessary therefore to fit a lock to hold the truck in position. In many designs, operation of this lock prior to withdrawal of the truck, also automatically trips out the circuit-breaker. In the locked-in position, a hasp is available for padlocking to prevent unauthorised operation. Examples of truck type switchgear are shown in Figs. 4-9, 4-10 and 4-11.

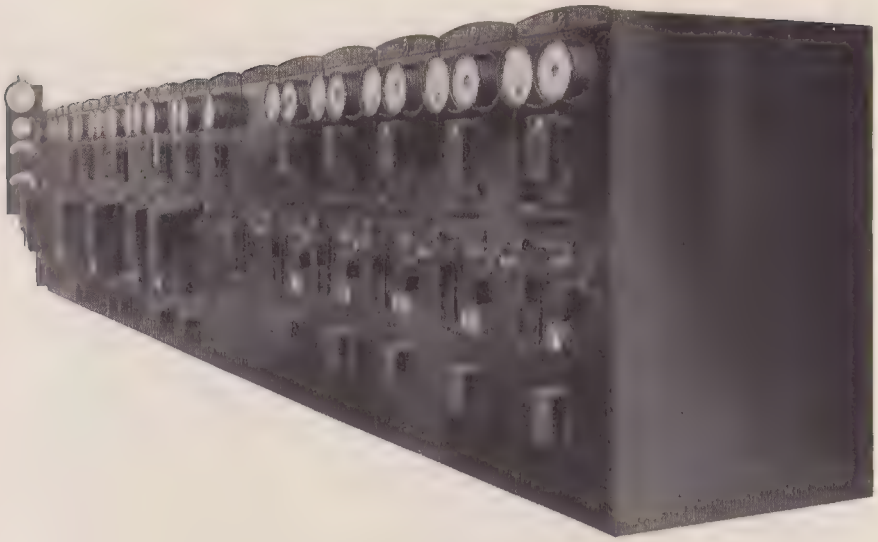


FIG. 4-9.—*Power Station Switchboard of Truck Type Units, with solenoid operated breakers for the generator circuits.*

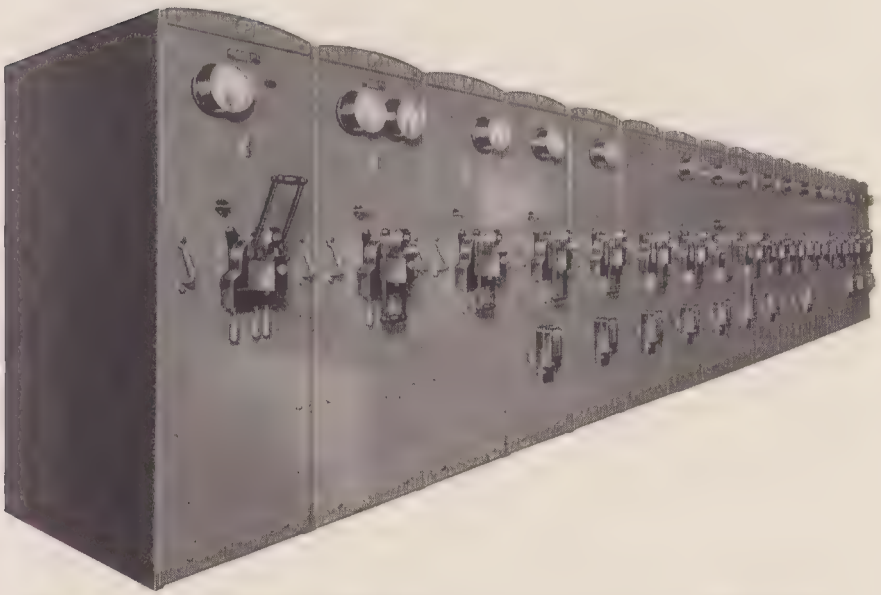


FIG. 4-10.—*Substation Switchboard of Truck Type Units. Note Castell Key Interlocks on the three left hand units.*

FIG. 4-11.—*Truck Type Switchboard installed in a mine, with duplicate busbars arranged for plug change. Note isolator for earthing the cable through the circuit-breaker.*

In the latter provision is made for cable earthing. This is accomplished by means of the isolating switch seen above the circuit-breaker. The final operation of earthing the cable is by closing the circuit-breaker, thus ensuring safety should a live cable be inadvertently earthed.

Another form of truck type switchgear is that where isolation is vertical as opposed to horizontal as so far described. This type differs only in that the current transformers (and where fitted, the voltage transformer) are not accommodated in the moving portion. A typical unit is shown in Fig. 4-12. Isolation is by means of two jack screws operated by a handle from the front. The circuit-breaker rides up or down on channel runners and is supported on two side arms.

As with the horizontal draw-out truck, shutters automatically cover the isolating contacts on the fixed structure with the circuit-breaker lowered. This design has an advantage that in order to examine the circuit-breaker contacts, no separate tank lowering device is required, as by lowering the circuit-breaker to isolate and removing the tank bolts, the circuit-breaker top plate and contacts can be raised, leaving the tank behind on the base of the carriage. This is shown in Fig. 4-13.

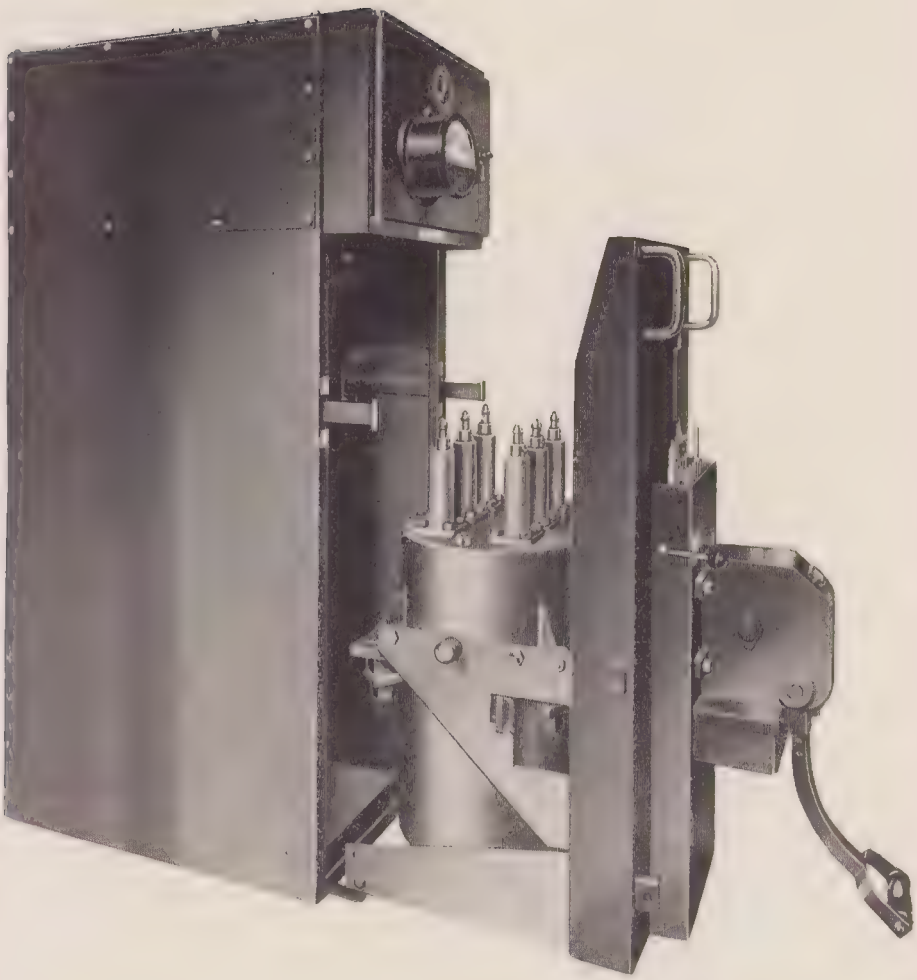


FIG. 4-12.—*Vertical Isolation Metalclad Unit, Air Insulated (J. & P., Ltd.).*

Typical examples of switchboards built in this type are shown in Figs. 4-14 and 4-15. From these it will be noted that the various instruments and relays are mounted on a hinged door above the circuit-breaker handle.

The upper limits of truck type switchgear are generally 11 kV and 250 MVA. The advantage of the drop-down type is that when isolated the space occupied is only that of the unit when in service. Space in front is required for withdrawal for maintenance and adjustments, but this is not so great as with the horizontal type. Both types can be placed back to a wall, no rear access being necessary—cables can be made off from the front. Both types have all connections and busbars in air although recourse to taping or moulded insulation is made in certain circumstances.

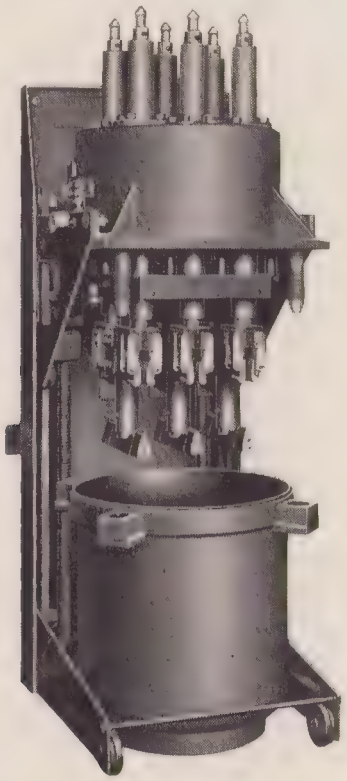


FIG. 4-13.—*250 MVA Metalclad Unit Breaker opened for inspection on carriage.*

(*c*) METALCLAD FILLED TYPE.

No design of switchgear is more essentially British in conception and design than the type which we may call "filled type." More commonly it is referred to as "compound filled," but as other media are used, particularly at the higher voltages, the term "filled type" is perhaps more embracing. Away back in 1906 the type was first introduced by Messrs. A. Reyrolle & Co., Ltd., and it is of interest to note that the essentials of the earliest designs are still retained in present day equipments although

naturally improvements have been made in details. Today, nearly all British switchgear makers produce designs of filled gear in one form or another. The range of such gear extends to the highest voltages and includes 132 kV (the outdoor metalclad switchgear at the Tongland sub-station—Central Electricity Board—Messrs. A. Reyrolle & Co., Ltd.).

In contrast, Continental practice continues along the line of open type gear on two, three, or even four floors. The continuance of the open type

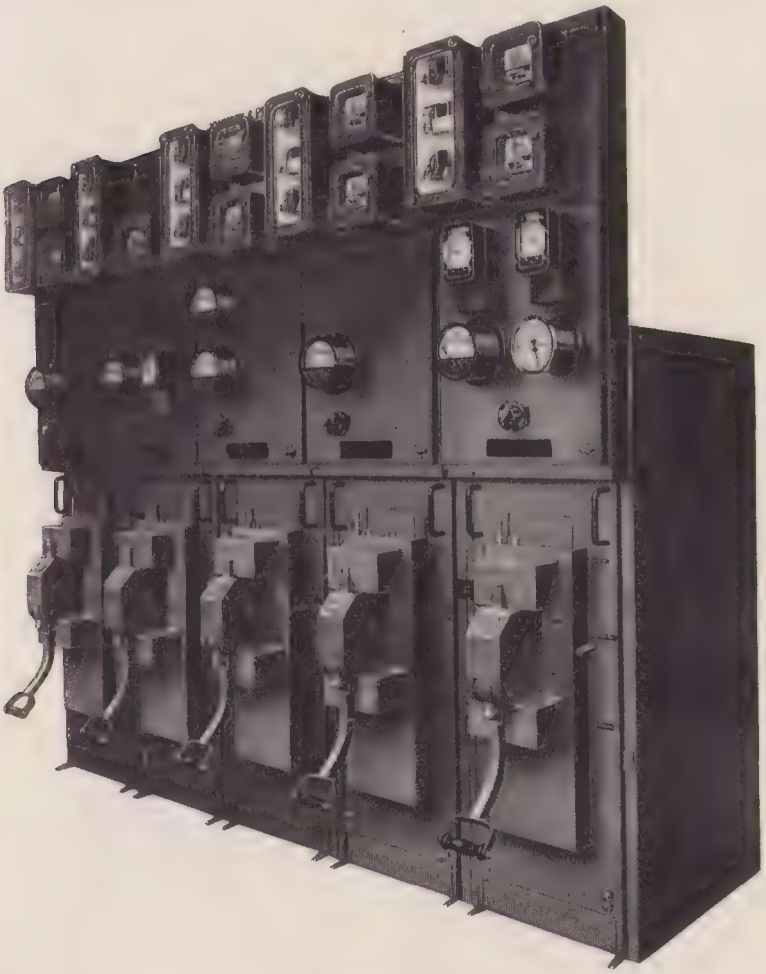


FIG. 4-14.—*Metalclad Air Insulated Switchboard, Vertical Isolation, with 16 inch round tank circuit-breaker* (*J. & P., Ltd.*).

on the Continent may be due to the fact that the type of circuit-breaker developed there in the past few years, *e.g.*, expansion, air blast, etc., does not so readily lend itself to metalclad designs. American practice has been influenced to some extent and while the volume of filled type switchgear

used in the U.S.A. is not great in relation to the total, there are American designs which approximate very closely to British designs.

In other American designs, a type which may be described as half cubicle, half metalclad, finds favour.

Filled type switchgear may be said to have the following advantages :—

(*a*) Greater safety to life.
(*b*) Saving in space.
(*c*) Reduced hazards due to fire, busbar faults, etc.

The first of these is due to total enclosure in earthed metal, coupled with complete interlocking safeguards. These interlocks can be more readily

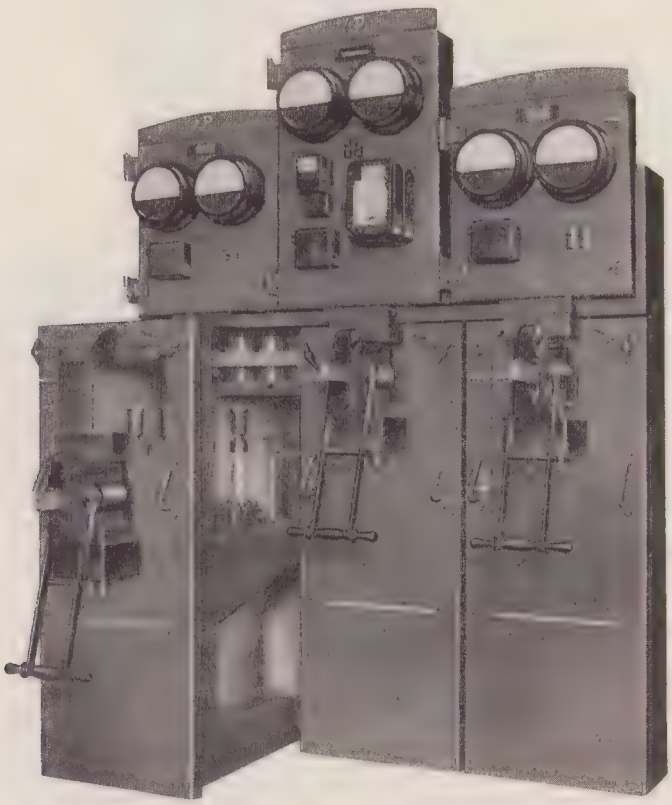


FIG. 4-15.—*Metalclad Air Insulated Switchboard, Vertical Isolation, with 20 inch round tank circuit-breaker.*

applied to the type of gear in question and clearly make for safety and reduce the possibility of incorrect operation.

Saving in space depends on the size of the gear and as the voltage and breaking capacity increase, so the saving becomes more marked. For comparison we may consider the alternative type known as cellular, in which a cubicle is built of pre-cast concrete slabs. This type would, in many cases, take up 75 per cent. greater cubic space than filled type gear

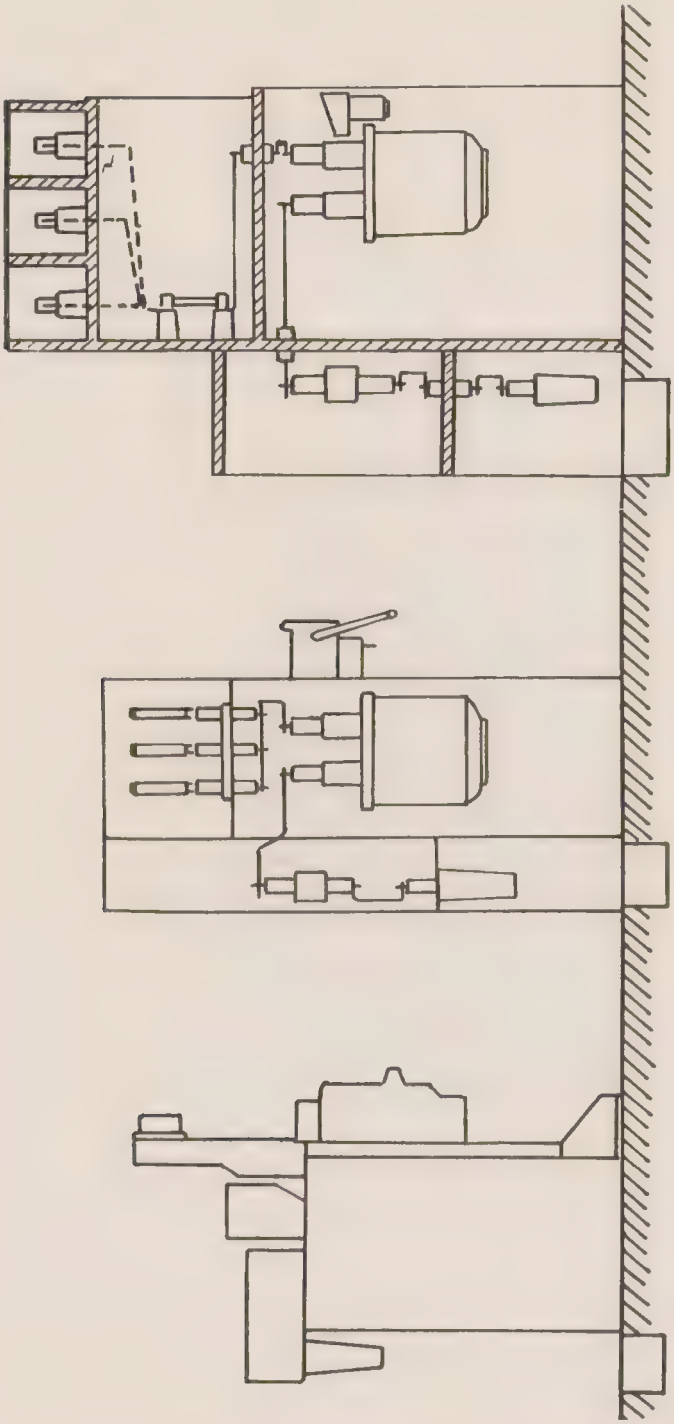


FIG. 4-16.—*Comparative space requirements of 250 MVA, 11 kV gear, for filled, cubicle and stone cellular types.*

for equal duty. Floor space may be 25 to 30 per cent. greater, while when the voltage reaches 33 kV (which may be regarded as the upper limit for cellular gear) the height may be twice that of filled gear or even more with duplicate busbars.

That this should be so can best be understood by a comparison of the 33 kV clearances necessary in air and in filled types.

	In Air	In Compound
To earth	8·75 ins. ..	2·5 ins.
Between phases	14·0 ins. ..	3·5 ins.

Fig. 4-16 will serve to illustrate the difference in space requirements for a 250 MVA switchgear unit for use on 11 kV as between filled type, cubicle and stone cellular.

The third point, that of reduced hazards, is important, noting that in metalclad design each unit is totally segregated from its neighbour by the metal enclosure.

This helps to prevent the spread of damage which may occur at one unit to another. Busbar faults are less likely by reason that the filling medium acts firstly as additional support to the busbars on the occurrence of heavy through currents, and secondly it excludes the possibility of extraneous matter getting across the bars, or to earth.

As against these advantages, it is reasonable to set down those which may be claimed for open type gear.

Firstly there is the claim that free access is possible (with suitable precaution) to all connected apparatus in case of trouble. This permits also of more readily increasing the busbar section if this becomes necessary with added load and of easy changing of current transformers.

Secondly, the cost of metalclad filled type gear is greater than that of the open types. Very often this is the only reason for the choice of the latter.

Finally, filled type switchgear presents a problem of some difficulty for the higher current ratings (2,000 amperes), and particularly in busbar construction where the bars may need to have a capacity of up to 4,000 amperes. The problem, while difficult, is more readily overcome in the open type, although this requires greater space.

As a general description, all forms of filled type switchgear comprise two main parts, one being a fixed stationary structure which comprises the busbars, current and voltage transformers, instrument and relay panels, and the fixed isolating devices, while the other part is a movable structure comprising the oil circuit-breaker with its operating mechanism, a carriage for the circuit-breaker, and, when required, selector switches for busbar selection.

In detail, this general description is varied as between the type of gear where the circuit-breaker is isolated by movement in a horizontal plane and the type where isolation is carried out vertically, as between the disposition of the busbars in relation to the circuit-breaker, and as between the methods adopted for the selection of busbars in duplicate busbar units. In all types provision is necessary for the coupling of the movable into the fixed structure, involving connection or disconnection of both primary and secondary circuits together with safeguarding interlocks.

A description of the individual items which go to make the whole can most conveniently be given under the headings :—

(1) Horizontal versus Vertical Isolation.
(2) Means of busbar selection.
(3) Interlocking Safeguards.
(4) Busbars.
(5) Current Transformer Enclosures.
(6) Voltage Transformer Accommodation.
(7) Miscellaneous Details.

Horizontal versus Vertical Isolation.

From time to time many specious arguments have been advanced in favour of one form of isolation against the other. Many of these have

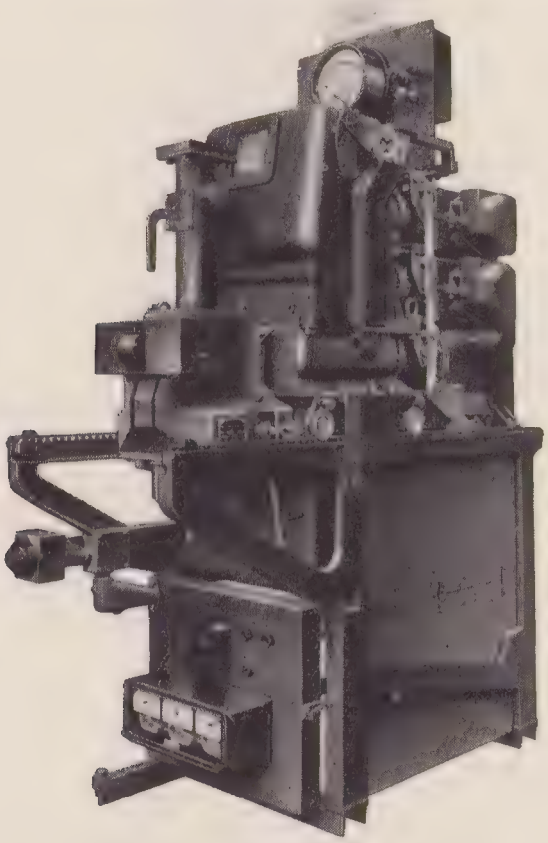


Fig. 4-17.—*Typical Unit with Horizontal Isolation (The English Electric Co., Ltd.).*

little justification in fact, but nevertheless there are certain advantages with both types. Firstly let us distinguish between the two. Fig. 4-17 shows a typical unit arranged for horizontal isolation, while Fig. 4-18 shows a unit with vertical isolation. In the former it will be noted that the fixed structure comprises a pair of side supporting frames which, in

addition to providing support for busbar and current transformer chambers, act as runners for the circuit-breaker. An accurate track is provided by means of a toothed rack, and through a racking handle and pinion, the circuit-breaker is moved along the track. The racking handle is usually fitted with a reversible ratchet to determine the direction of circuit-breaker movement. The racking handle lends itself to attachments for interlocking very readily.

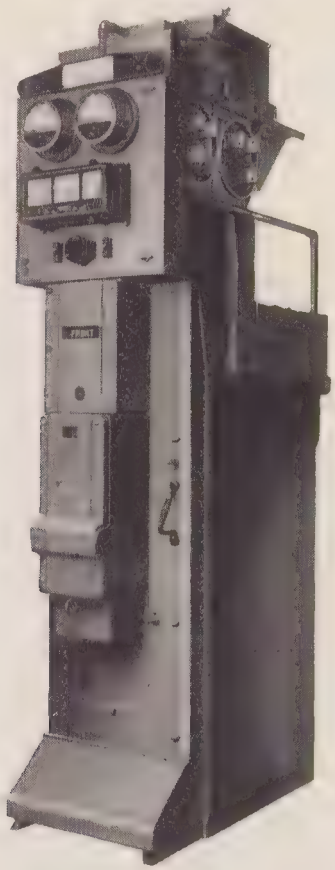


FIG. 4-18. — *Typical Unit with Vertical Isolation (J. & P., Ltd.).*

In the vertical isolation type, again we have the fixed structure but in the form of a housing of steel plate. Within this housing the breaker may be raised or lowered through the medium of jack-screws, or by a worm gear device.

A study of the illustrations will show that in the case of horizontal isolation, removal of a circuit-breaker from its frames involves either the use of a crane, or as is more usual in the smaller range, a transport carriage. Similarly, removal of the circuit-breaker tank demands a lifting and lowering device, and the transport carriage is usually made to fulfil these requirements. On the other hand a circuit-breaker in the vertical isolation type

is not only raised and lowered on its self-contained carriage but can be wheeled away complete. The same lifting mechanism is used for tank removal and replacement by bodily movement of the breaker top-plate with bushings and contacts. This procedure is illustrated in Fig. 4-19, which shows a circuit-breaker complete with selector switch for duplicate busbars.

FIG. 4-19.—*Withdrawable Circuit-Breaker Carriage, tank lowered (J. & P., Ltd.).*

It may be claimed in respect of the horizontal type that it requires less manual effort in isolation and that interlocking is simpler. The horizontal plane of the side frames is an aid to accurate alignment without the elaboration of guides. Against this the vertical type takes up less floor space in service and requires a smaller gangway for manipulation. It requires no compound filled hoods above the circuit-breaker to connect the latter to the primary disconnecting devices. This permits the use of standard terminal arrangements for the circuit-breaker, reduces the length of connections, and the possibility of compound leakage into the circuit-breaker.

When duplicate busbars are used, and the selection is by means of oil-immersed selector switches, the horizontal isolation unit lends itself readily to accommodation of the chamber to house the selector switches on the top plate of the circuit-breaker, and does not unduly increase the overall height of the complete unit.

In the vertical type, the height of the unit does increase, but it is often possible to give increased headroom rather than floor area.

The positioning of the busbar chambers is important. Horizontal isolation permits these to be to the rear and not immediately over the circuit-breaker. The two chambers in the case of duplicate busbars are usually placed one above the other, and in this arrangement the lower chamber is not easy to remove if the need arises. With vertical isolation, the busbar chambers are almost invariably above the circuit-breaker, or very nearly so.

Arguments have been offered against this on the grounds that disaster affecting the circuit-breaker will automatically affect the busbars. Such argument has little point today, when proved breakers are the rule rather than the exception. Against this may be placed the advantage of being able to place the busbar chambers side by side, enabling either to be removed without difficulty.

The conclusion may be reached from the foregoing that both horizontal and vertical isolation have features distinctive to the type, that both have advantages and disadvantages, and that both are approximately equal in these respects. Both have been proved in British designs and it is of interest to note that approximately one-half of the manufacturers make one type, and one-half the other.

Means of Busbar Selection.

As opposed to other types of switchgear, the metalclad type of gear has been much more readily adapted to various methods of duplicate busbar selection. In the earliest designs, selection was by means of removable plugs. In this design, a set of three plugs is supplied capable of being screwed into either an upper or lower set of fixed orifices, with the circuit-breaker in the isolated position. It is a method which involves climbing to get at the plugs and then handling them in this awkward position. For the lower values of normal current the method is least costly but is not to be recommended for higher currents. They are usually only adaptable to the horizontal type of isolation.

The plug-changing method is naturally an " off-load " form of busbar selection and is illustrated in Fig. 4-20.

By far the most popular form of busbar selection is that carried out by means of an oil-immersed throw-over switch. It can be made either " off-load " or " on-load," as shown in Figs. 4-21 and 4-22.

From Fig. 4-22 it will be noted that the blade, in the shape of a fan, is arranged to make before the break.

The isolator, in triple pole ganged form, is accommodated in an oil-tight chamber mounted immediately above the oil circuit-breaker (see Fig. 4-30).

With " on-load " selection by this method, it is usual to provide an interlock with a busbar coupling switch so that the latter must be closed first. Where certain generating plant may be connected to one or other set of busbars, synchronising across the busbar coupler is usual and is

arranged so that the operation of synchronising must be performed before closing the breaker. The interlocked isolator also ensures that the busbars cannot be coupled normally through the isolator.

Fig. 4-27 illustrates a cross section of a complete vertical isolation unit with on-load selector switches.

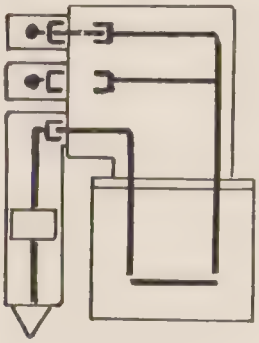


FIG. 4-20.

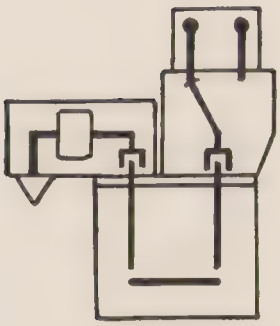


FIG. 4-21.

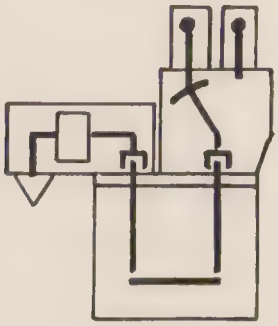


FIG. 4-22.

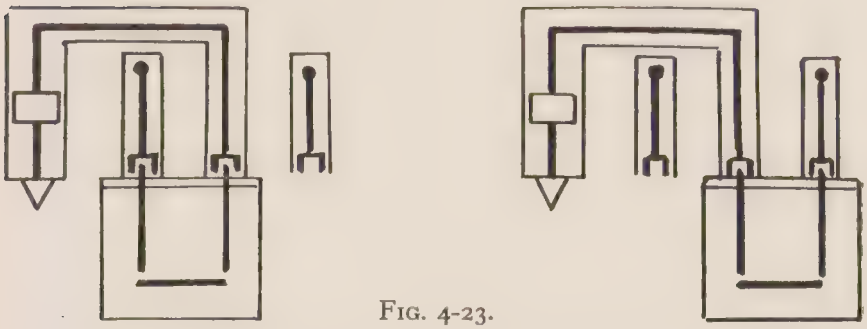


FIG. 4-23.

The disadvantage of the oil immersed selector is that it adds to the quantity of oil per unit. It also involves a common connection to both sets of bars within the selector switch chamber.

At an increase in first cost, these disadvantages may be overcome in the "off-load" type by the use of a transfer circuit-breaker. In this,

the circuit-breaker is first isolated completely from one set of bars, bodily moved, and then reconnected to the second set of bars. In the vertical isolation type, this involves lowering the breaker unit, its movement backward or forward on rails provided, and then raising into another set of bars. This is illustrated in Fig. 4-23.

In the horizontal isolation type, it is usual to instal two rows of fixed structures back to back, the circuit-breaker being in service on one row or the other, as shown in Fig. 4-24. To move the circuit-breaker a transport

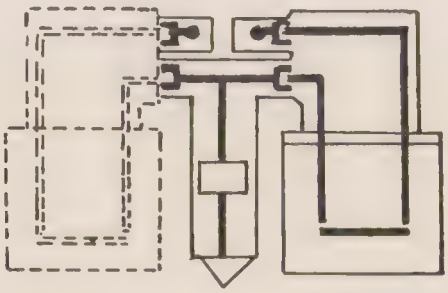


FIG. 4-24.

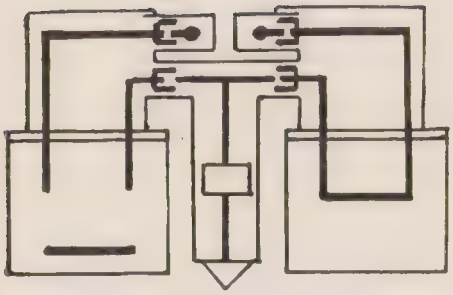


FIG. 4-25.

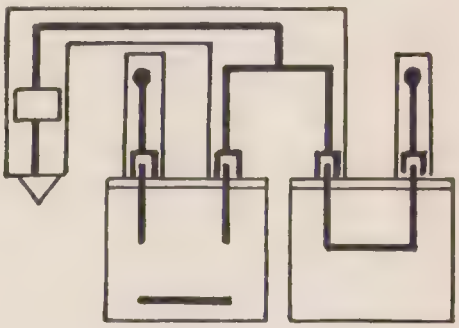


FIG. 4-26.

carriage is necessary, or if not available, a crane. The transfer method of selection is obviously only suitable for " off-load."

A variant of the transfer breaker method is to use two separate circuit-breakers, a method ruled out on the score of cost in all except the largest installations and at the higher voltages.

This is an " on-load " method and necessitates interlocks between circuit-breakers so that one only remains closed. Fig. 4-25 illustrates this method as adopted in horizontal isolation, while Fig. 4-26 depicts the method in vertical isolation.

A further method is that where a specially designed circuit-breaker has two sets of moving and fixed contacts with a common centre point.

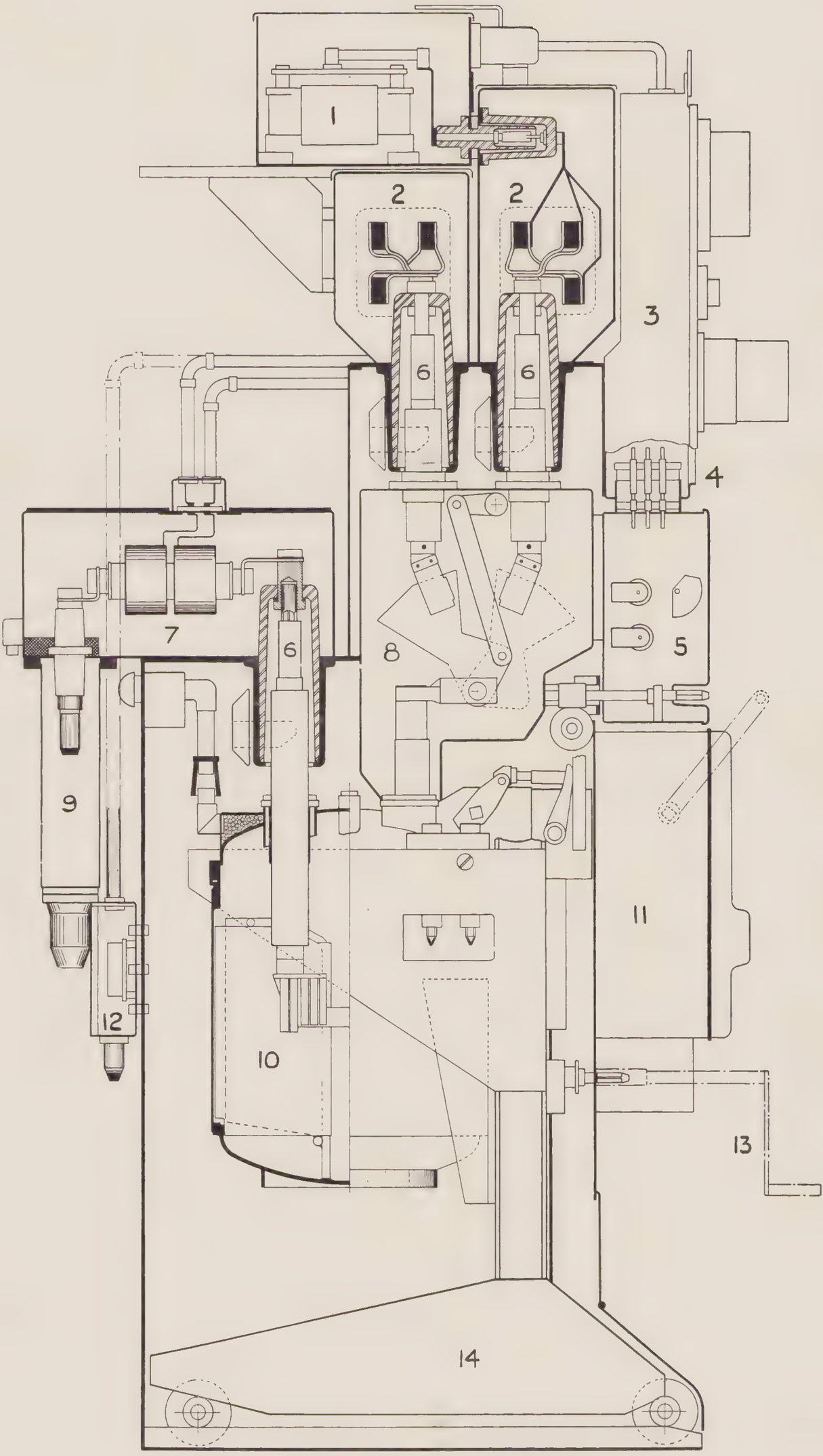


FIG. 4-27.—*Cross-sectional view of Duplicate Busbar Vertical Isolation Filled Type Switch Unit.*

REFERENCES

1 – *Plug-in type Voltage Transformer*
2 – *Busbars*
3 – *Instrument and Relay Panel*
4 – *Secondary Plugs and Sockets*
5 – *Operating Mechanism for Selector Switches and Chamber for Auxiliary Switches*
6 – *Primary Circuit Isolating Plugs*
7 – *Current Transformers*
8 – *Selector Switches*
9 – *Cable Box*
10 – *Oil Circuit-Breaker*
11 – *O.C.B. Operating Mechanism*
12 – *Multicore Cable Box*
13 – *Raising and Lowering Handle*
14 – *Carriage*

It is equal to two separate circuit-breakers but has the disadvantage of a specially made circuit-breaker. Fig. 4-28 will serve to illustrate the type.

Finally we have a method which permits a circuit-breaker stem with

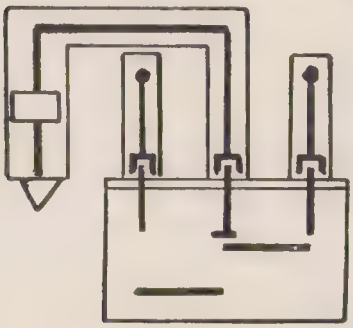


FIG. 4-28.

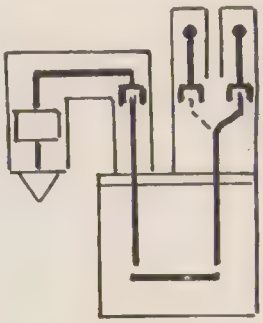


FIG. 4-29.

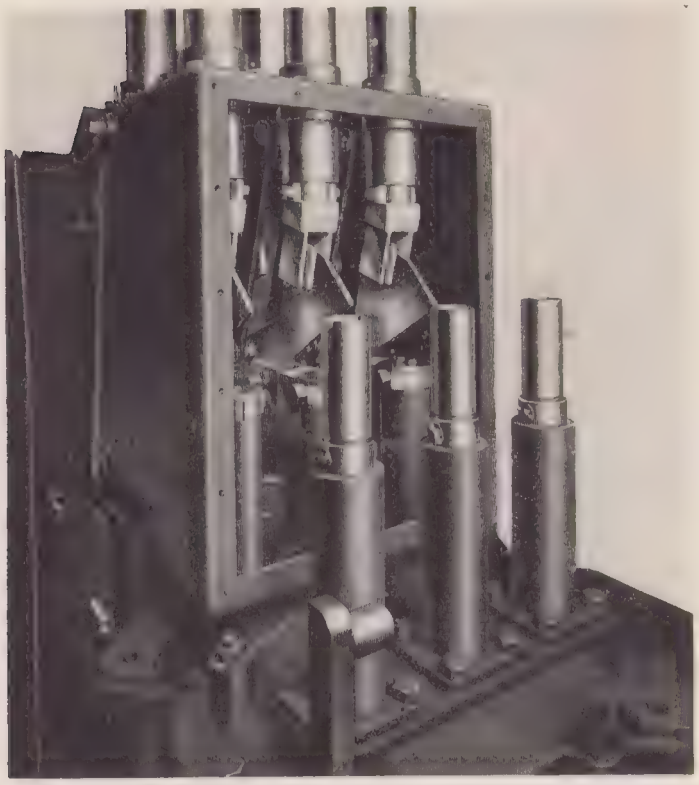


FIG. 4-30.—*Fan Blade Selector Switch, " on-load " type.*

plug contact to be rotated through 180 degrees to make contact with one set of bars or the other. This is shown in Fig. 4-29 and it is only suitable for " off-load " selection.

Of the foregoing, the oil immersed selector method has perhaps been most favoured for medium power and substation installations. Figs. 4-30 and 4-31 illustrate designs of this type.

FIG. 4-31.-*Rearview of Circuit-breaker carriage showing selector switch chamber.*

INTERLOCKING SAFEGUARDS.

It has been claimed that metalclad switchgear lends itself to complete interlocking in a way that does not so easily present itself in other types. These interlocks usually provide that :—

(*a*) The circuit-breaker can only be closed when it is in the fully withdrawn or fully plugged-in position. Any attempt to isolate or plug-in the circuit-breaker when in a closed position must immediately cause it to trip open.

(*b*) The circuit-breaker tank can only be removed when the breaker is in the open and isolated position.

(*c*) It is not possible to re-connect the circuit-breaker to the busbars with the tank off.

(*d*) In plug-changing designs, all three plugs must be in correct position, *i.e.* it must not be possible to plug the circuit-breaker home with two plugs connecting to one set of busbars and the third plug connecting to the other.

(*e*) Automatic shutters must cover all live sockets when the circuit-breaker is isolated or when a voltage transformer is withdrawn. These shutters must be capable of being locked in a closed position.

(*f*) Voltage Transformer fuses (primary) usually oil-immersed in the transformer tank, must be inaccessible until the transformer is isolated.

BUSBARS.

The construction of busbars and busbar chambers in solid filled types of switchgear demands very careful design. Much lower current densities in the copper are necessary to avoid excessive temperature rise, the limits of which are given in B.S. 159 as 50 deg. C. Unless a user is very sure of his facts, it is unwise of him to specify densities or sections, or both, and he should content himself by stating the current rating he requires or give such facts as will enable the maker to offer the best section.

Current densities vary with designs and designers, but in general figures such as the following are a good average :—

Up to	500	amps.	....	....	1,000/1,200	amps.	per	sq. inch.
,, ,,	1,000	,,	....	....	750	,,	,,	,, ,,
,, ,,	1,500	,,	....	....	500	,,	,,	,, ,,
,, ,,	2,000	,,	....	....	350	,,	,,	,, ,,
,, ,,	2,500	,,	....	....	300	,,	,,	,, ,,
,, ,,	3,000	,,	....	....	250	,,	,,	,, ,,

In considering the above figures, it should be noted that up to 2,000 amps. the busbars usually take the form of plain laminations as used in other types of switchgear. For higher ratings special designs of busbar become necessary, involving subdivided bars or bars forming a hollow square, or equal formation.

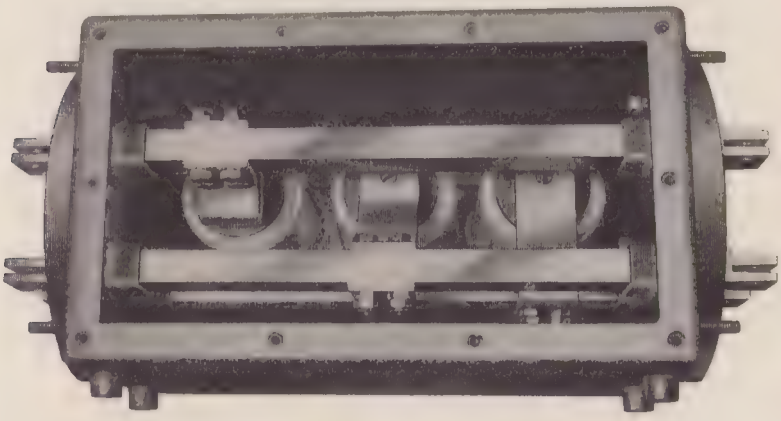


FIG. 4-32.

Busbar Chamber before compounding.

The use of compound as a filling medium excludes air from the chamber and permits reduced clearances. It forms an excellent additional support for the busbars against the forces of short-circuit but, unfortunately, compound is a thermal insulator. Excessive temperatures have to be avoided and careful tests are necessary to check this. As the bars are inaccessible, thermo-couples are used to obtain temperature measurements.

Apart from heating, the designer must bear in mind that phase bars placed close together increase the losses due to proximity effect. Placed far apart to avoid this, a greater volume of compound is needed,

thereby reducing thermal capacitance and increasing the ultimate temperature. Bars placed as close to the surrounding casing as possible is the ideal for heat dissipation.

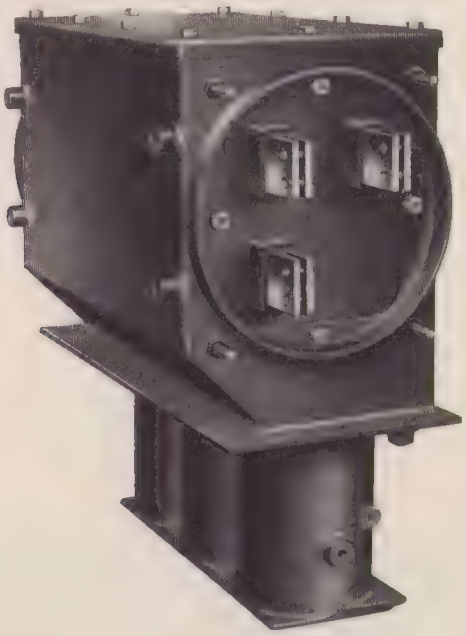


FIG. 4-33.

Busbar Chamber, showing isolating spouts and joint muff ring.

In the end, it is the *total* temperature which really matters, related as it must be to the ability of insulating materials to withstand this temperature.

A typical busbar chamber prior to filling with compound is shown in Fig. 4-32.

The process of filling a busbar chamber is one demanding care and cleanliness.

The formation of gas bubbles due to over-hot compound must be avoided and it is naturally essential that air should not be trapped to form pockets. Prior to pouring, the chamber must be pre-heated to prevent rapid cooling of the compound in contact with the metal of the chamber, and, incidentally, to remove all traces of moisture. Expansion space must be left in all compound chambers.

It is inherent in designs of filled type switchgear that joints between unit sections of busbar must be made on site. This involves the use of joint rings, or muffs, fitted after the copper joint plates have been fitted, and then filling with compound. It is necessary then to repeat here the procedure at the factory, of preheating the muff before pouring the compound, and carefully watching pouring temperatures.

In Fig. 4-33 the rim for taking the muff can be seen, while in Fig. 4-34 the muff has been fitted to one busbar chamber and joint ring.

The copper joint pieces between the busbars must be designed to avoid hot-spots, and be arranged to allow expansion under load conditions.

For the lower values of current, slightly elongated holes will often suffice ; at higher values, flexible joints become necessary.

Current Transformer Enclosures.

In early designs, the use of solid compound as a filling medium was extended to current transformer enclosures. Later it was realised that this had several disadvantages.

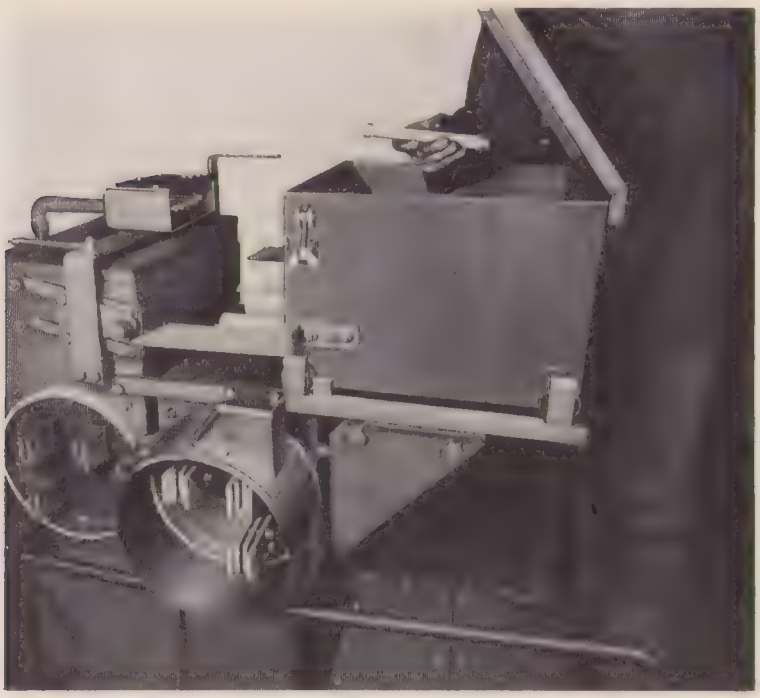


Fig. 4-34.
Busbar Chamber fitted with joint muff. Also illustrating busbar voltage transformer.

Chief among these was the difficulty which occurred when the need for transformers of a new ratio arose. An increase in circuit capacity demands new ratio current transformers and while the primary conductors and the circuit-breaker are often of ample capacity to cover the increase, the current transformers must be changed. If these are embedded in compound, this must be removed, a tedious and difficult operation if carried out on site.

This led to the present day practice which provides for oil filled current transformer chambers. The most suitable oil is a thick, heavy one, not so liable to leak through joints (which are often vertical) but which will readily empty through a drain plug.

Owing to the space saving features of filled type switchgear, accommodation for a large number of current transformers is not always possible, particularly on smaller units. Where possible, ring (bar primary) transformers are used and two or even three of these may be mounted on a common primary bar within a small space. A typical arrangement of this is illustrated in Fig. 4-35.

In a vertical isolation type, an additional current transformer chamber can if necessary be placed in line with the cable outlet, as shown in Fig. 4-36.

FIG. 4-35.
Current Transformer Chamber before filling.
Note bar primary transformers.

VOLTAGE TRANSFORMER ACCOMMODATION.

Perhaps the most difficult item to accommodate with satisfaction in any filled type switchgear is the voltage transformer. This is particularly so in the case of busbar transformers and more so in the case of duplicate busbars.

When, as in horizontal isolation units, duplicate busbars are mounted one set above the other, it is often arranged that the busbar voltage transformer occupies a separate set of side frames along which a plug-in transformer may run, as in Fig. 4-37.

In horizontal types, extended busbar chambers, as shown in Fig. 4-34, will permit of busbar voltage transformers being mounted on the top of the unit obviating the need for increasing the overall length of the switchboard.

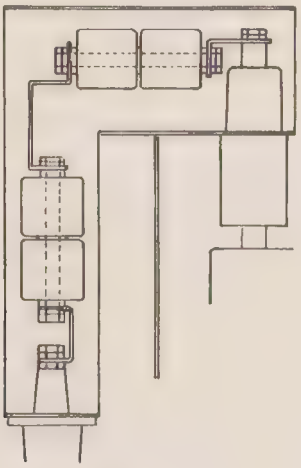


FIG. 4-36.

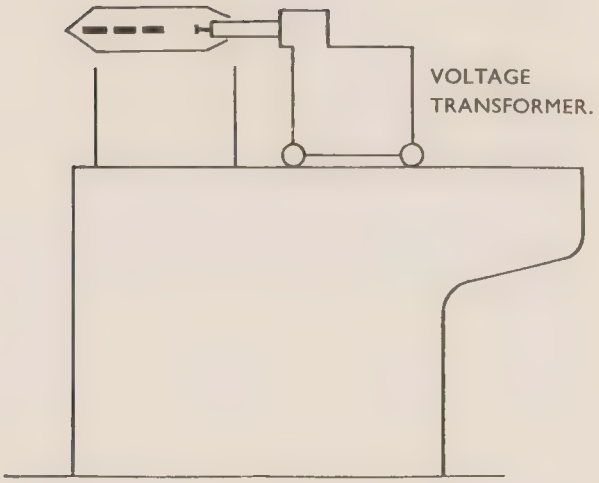


FIG. 4-37.

Feeder voltage transformers may be accommodated as shown in Fig. 4-38, which shows typical arrangements for both vertical and horizontal isolation.

Miscellaneous Details.

Among the miscellaneous details which may usefully be considered are:

(1) Automatic Shutters
(2) Secondary Plug Contacts
(3) Test Jumpers
(4) Cable Earthing Devices

Automatic Shutters.

In all conventional designs of switchgear which incorporate means for isolation by either withdrawing the circuit-breaker vertically or horizontally, it is usual to provide shutters which automatically cover the plug orifices when the circuit-breaker is isolated.

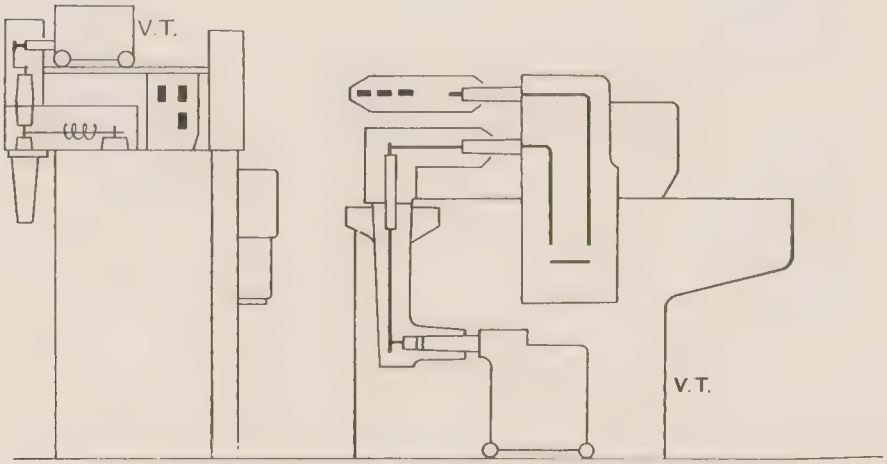


Fig. 4-38.

These shutters are, conversely, automatically opened as the breaker is plugged home again. Means should be provided to enable either or both of the shutters (cable side, or busbar side) to be padlocked in position. More particularly, it is essential that the busbar spout shutters be capable of padlocking in the closed position, in order to provide safety to men working on a unit, probably with the busbars alive to other units, and with the cable side spouts uncovered to permit the cable to be earthed.

It is equally important that where plug-in voltage transformers are employed, automatic shutters should cover the live sockets when the transformer is removed, as it must be for fuse renewal.

Secondary Plug Contacts.

In any form of gear with means of isolation, it is necessary that when the primary conductors are isolated, the secondary connections (current and voltage) should be simultaneously disconnected.

This is done by means of a set of secondary plugs and sockets. A typical arrangement as used in vertical isolation gear is shown in Fig. 4-39.

In this design, a circular plug and socket is used, but in others the plugs of flat strip make contact into sockets similar to the contacts of a knife switch. In both, good contact and alignment is a first requirement, bearing in mind that a single poor contact can be the cause of valuable protective gear failing to function when most needed. Fig. 4-40 shows the interior wiring of an instrument and relay panel, with connections to the secondary sockets at the bottom of the picture.

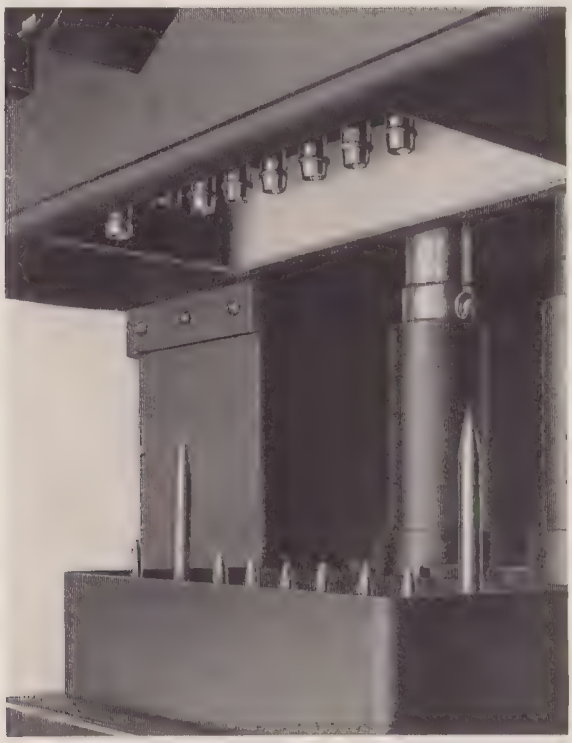


FIG. 4-39.
Secondary Plug Contacts on Vertical Isolation Type Unit.

TEST JUMPERS.

It follows that when all secondary connections are isolated as above, it will be impossible to test out various circuits, such as protective, unless means are provided to re-connect the secondary connections without re-connection of the primary circuit. This is accomplished by the use of a test jumper box, designed to fit between the male and female contacts in the isolated position. In electrically operated breakers, means must be provided to complete the solenoid coil circuit.

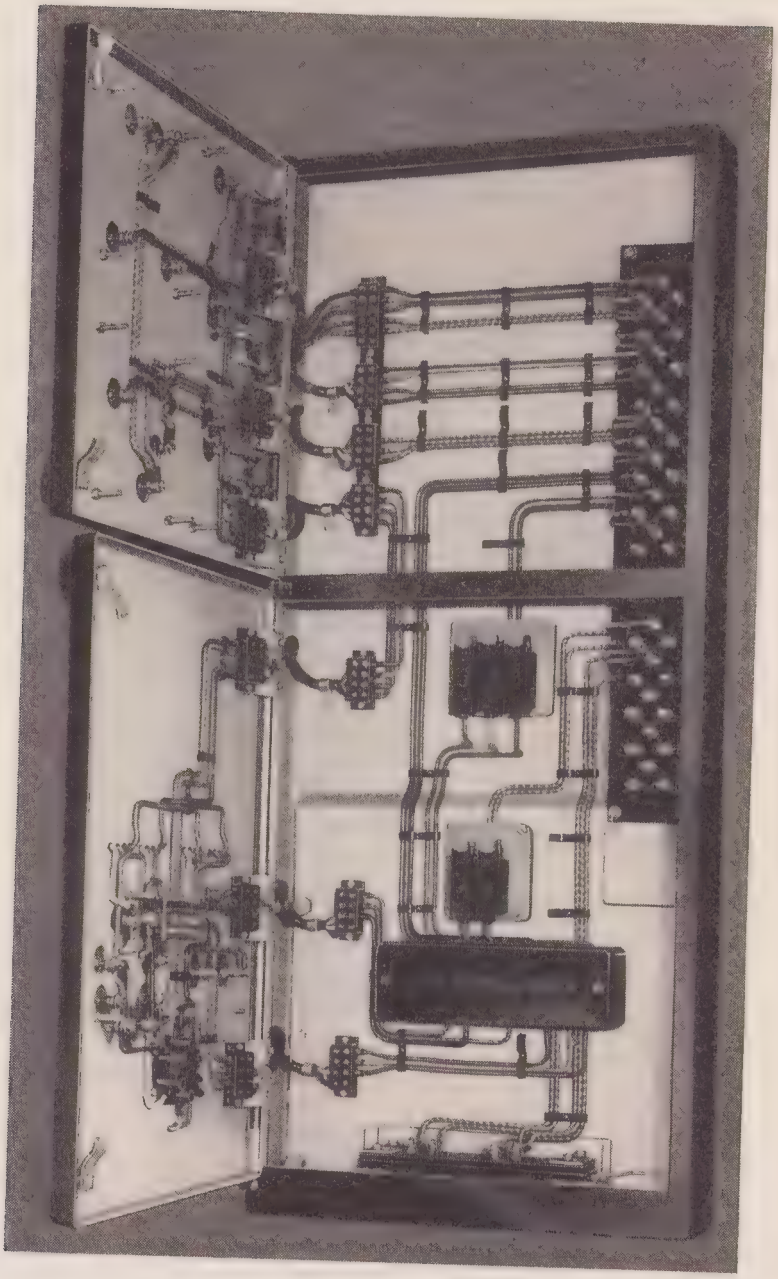


FIG. 4-40.
Interior of Relay Panels

CABLE EARTHING DEVICES.

In the interests of safety, the earthing of a cable is normal practice prior to work being carried out on any cable.

It is essential that the final operation of earthing the cable should be done through the oil circuit breaker, to give maximum protection against the possibility of earthing a "live" feeder. In general, this is done by first completely isolating the circuit-breaker. An earthing connection is then fitted to the three busbar stems of the circuit-breaker, and joined to the earth bar by flexible connection. Extended connectors are then fitted to the cable stems of the circuit-breaker, the extensions being of such length that contact can be made with the cable side isolating sockets while leaving the busbar stems still clear of the busbar spout shutters.

The following illustrations Figs. 4-41/4-49 are included here to indicate typical gear.

BIBLIOGRAPHY.

The Switchgear Handbook, Vols. 1 and 2, W. A. Coates and H. Pearce (Pitman & Sons).

"METALCLAD SWITCHGEAR, AUTOMATIC PROTECTION AND REMOTE CONTROL," H. W. Clothier, "Journal I.E.E.," 1932, Vol. 71, Pages 285-330.

The Calculation and Design of Electrical Apparatus, W. Wilson (Chapman and Hall).

"THE USE OF METALCLAD SWITCHGEAR FOR THE CONTROL OF POWER SUPPLIES," "M.A.I.E.E.," "The Electrical Engineer," July 22nd, 1938.

Switchgear Practice, Arthur Arnold (Pitman & Sons).

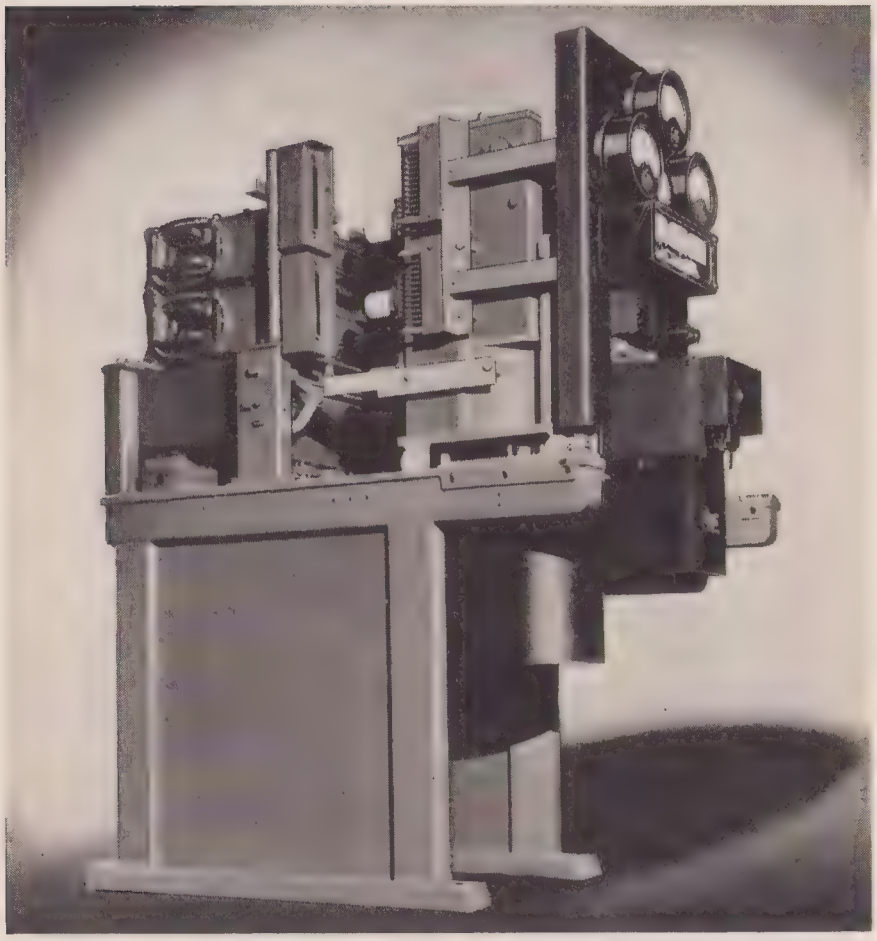


FIG. 4-41.

Horizontal Draw-out Type Metalclad Unit, B.T.H. Class MF44. Duplicate Busbars, 11 kV. Spring operated closing mechanism (The British Thomson-Houston Co., Ltd.).

FIG. 4-42.
One Section of Power Station Board, Duplicate Busbar, Solenoid Operated (Johnson & Phillips, Ltd.).

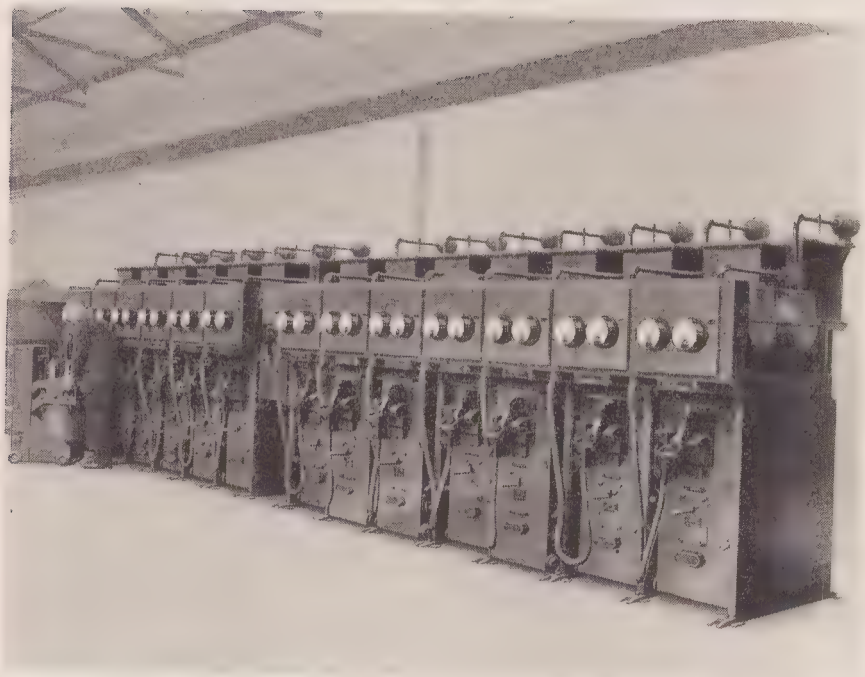


FIG. 4-43.
Duplicate Busbar Switchboard, Vertical Isolation
(Ferguson Pailin, Ltd.).

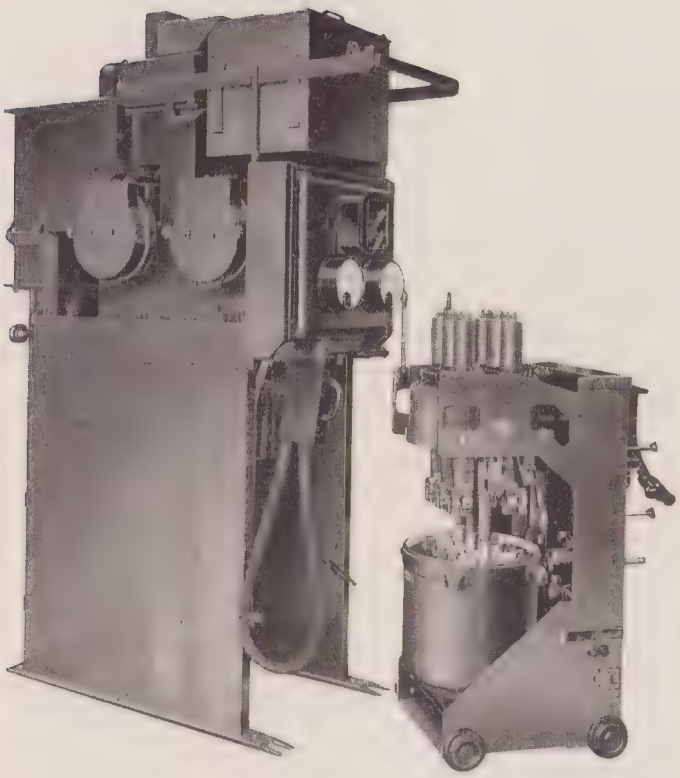


FIG. 4-44.
Typical Vertical Isolation Unit (Ferguson Pailin, Ltd.).

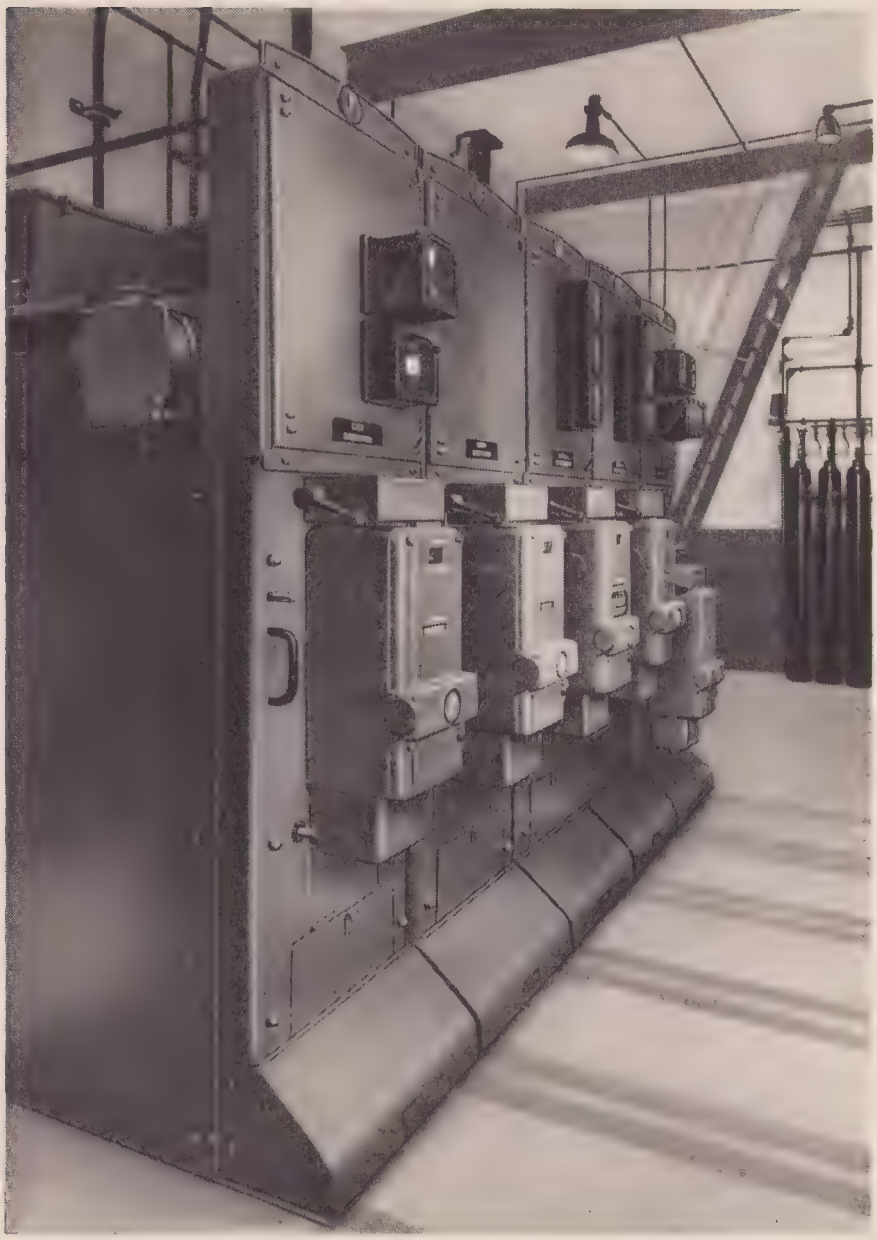


FIG. 4-45.
Substation Switchboard, Vertical Isolation
(Johnson & Phillips, Ltd.).

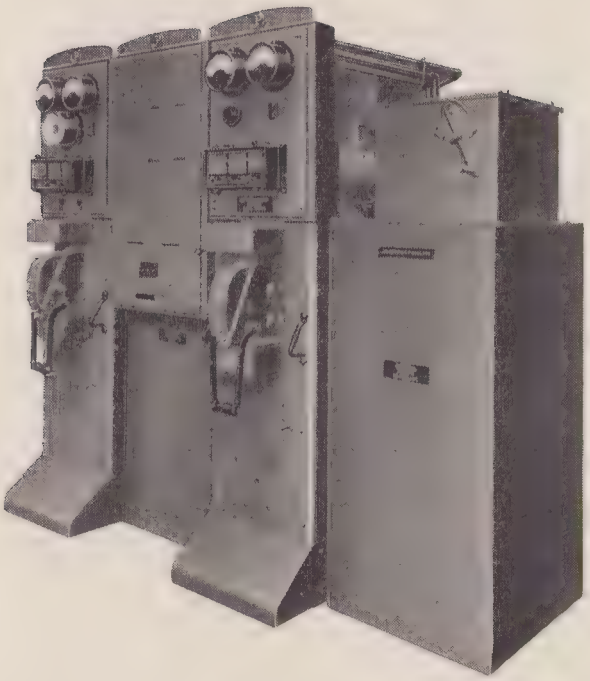


FIG. 4-46.
Showing Circuit-Breakers coupled to metering unit and (RH) oil-immersed isolator (J. & P., Ltd.).

FIG. 4-47.
Main Switchboard, Single Busbar, Vertical Isolation (J. & P., Ltd.).

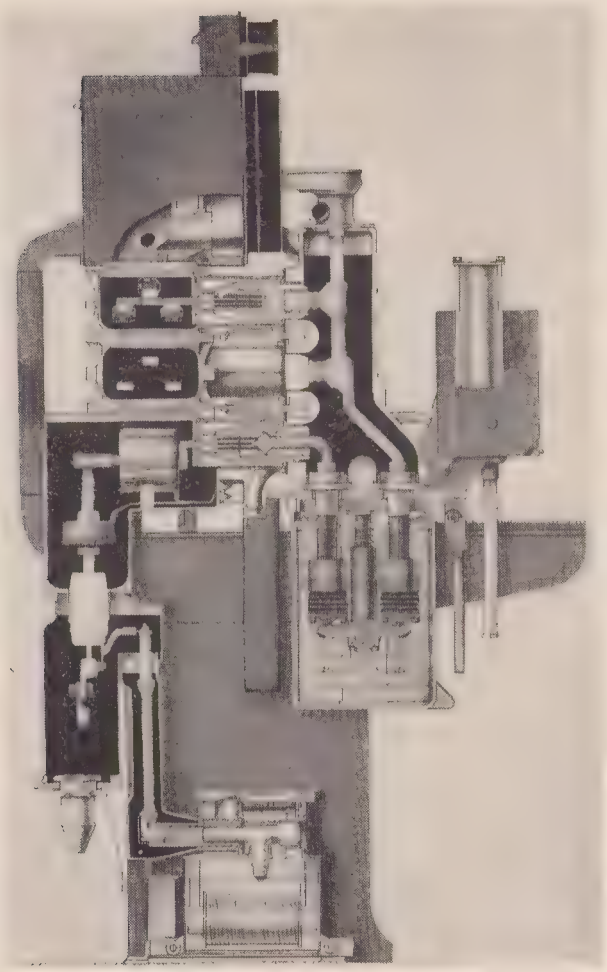


FIG. 4-48.
Cross-section of Horizontal Draw-out Compound Filled Metalclad Unit (A. Reyrolle & Co., Ltd.).

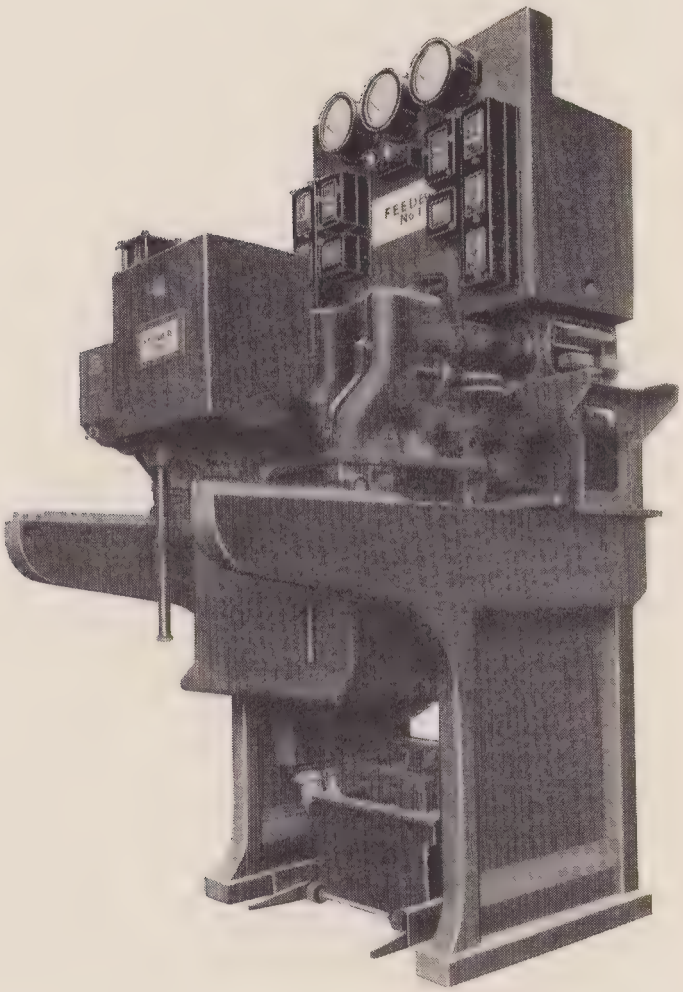


FIG. 4-49.
Horizontal Metalclad Unit (A. Reyrolle & Co., Ltd.).

CHAPTER V

HIGH VOLTAGE FUSED SWITCHGEAR

The oil-immersed switch-fuse is no novelty. For a number of years it has existed in various forms, some with, and some without, three-phase tripping. More recently attention has been given to the use of similar switchgear for the control of particular circuits where the use of an oil circuit-breaker is costly in relation to the importance of the circuit to be controlled. Earlier designs were, generally, of an outdoor type and found greatest application in controlling rural transformers or lines. Later developments both in England and America have been in the direction of indoor types, and attention has been focussed on such developments in two I.E.E. papers*, in which the use of the load-breaking oil-immersed switch coupled with h.v. h.r.c. fuses has been indicated for the future. The development has been coupled with the use of the now well known tripping fuse (see also Chapter XI) which operates to trip out the load-breaking switch where only one fuse functions.

Although the paper by Wood, as its title implies, deals extensively with low-voltage systems, consideration is also given to the means of protecting and switching the h.v. network, particularly transformers. The following extract is important.

> " The protection of transformers operating in parallel is normally assumed to involve relays. It is considered however that the distribution centre can be adequately protected against faults entirely by fuses, namely a high-voltage fuse and the low-voltage fuses already referred to.
>
> " The high-voltage fuse must be chosen to give discrimination over the low-voltage fuses under all circumstances, and must be of adequate rupturing capacity in accordance with the fault duty on the high-voltage system.
>
> " Oil or tetrachloride quenched designs are available but the sand-filled design is preferable.
>
> " A manually operated isolator on the h.v. side capable of breaking magnetising current is also necessary. The fuses can be combined with the h.v. isolator to give automatic three-phase isolation on single-phase faults and, if desired, the low-voltage isolator could also be intertripped."

The second paper, which deals extensively with the design and performance of h.v. fuses of the tripping type, powder filled, of high breaking capacity, includes the following statement.

> " In the load-breaking switch and fuse combination, the switch is simple and inexpensive, being relieved of the duty of rupturing short-circuit currents, a task now undertaken by the fuse. Also the current through the switch, instead of being the short-circuit current, is now limited by the melting current of the fuse, and this results in a lightening of the current carrying parts.
>
> " This simplification is possible because it is easier to embody provision for dealing with short-circuits and heavy overloads in a fuse rather than in a switch. The switch, dealing only with load

*See Bibliography papers by (1) *B. Wood* and (2) *K. Dannenberg and Professor W. J. John.*

switching operations and light overloads can be made as fully automatic as an ordinary circuit-breaker. The fuses will embody a striker-pin to ensure three-phase operation under fault conditions. An application for which this combination will be particularly suitable is that of controlling and protecting small and medium capacity transformers. Up to about 1,000 kVA at 11 kV, the orthodox oil circuit-breaker is more expensive than the transformer which it protects."

The conditions under which the use of h.v. fused switchgear are most favourable may well be reviewed. In the first place, it can be laid down

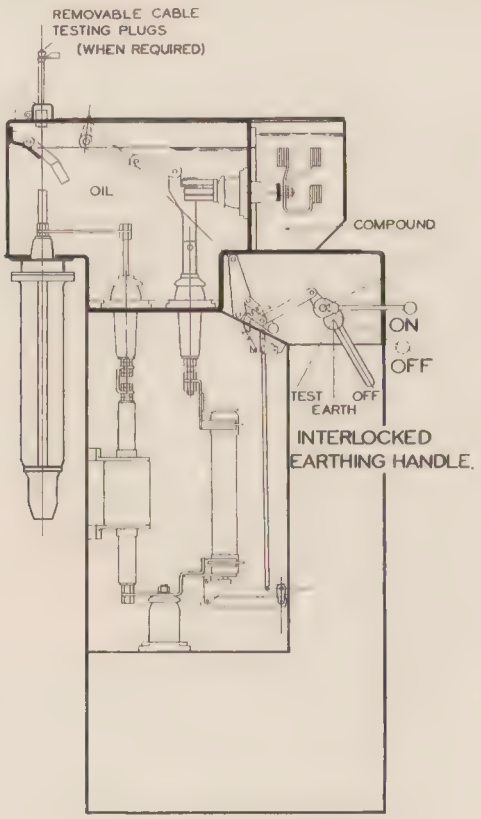


FIG. 5-1.
Cross-section of Oil Immersed Load-Breaking Switch with tripping fuses. 100 *amp.* 11 *kV range.*

that there can be no intention of superseding the circuit-breaker. In many applications the latter is indispensable. Where, however, the system conditions indicate breaking capacities of 250 and 350 MVA at 6·6 or 11 kV or 250 MVA at 3·3 kV, the cost of a circuit-breaker equipment is very expensive. For many circuits this has to be faced, but on the other hand, it is often necessary in an important main substation or distribution centre that one or more circuits on a switchboard must be for the control of auxiliary plant.

Examples of this are station services, auxiliary transformers, small rectifier circuits, etc. The capacity of circuits of this nature may only be small, *e.g.*, 50 or 100 kVA and yet, because of the high level of short-circuit at the switchboard, the control apparatus must have a breaking capacity equal to or greater than the short-circuit value. It is, then, for circuits of this type at the higher values of breaking capacity that the load-breaking switch with fuses is of value and most economical.

The foregoing implies that (*a*) the requirements shall be for the simplest circuit equipment without expensive relaying or metering, and (*b*) the design must be such as to line up with the normal form of circuit-breaker equipment to be used.

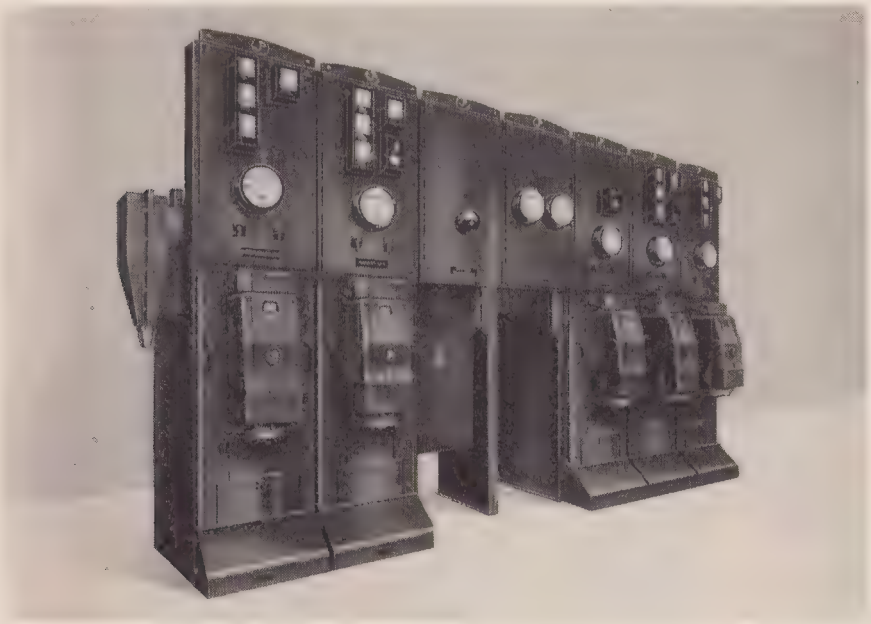


FIG. 5-2.
Metalclad Compound Filled Switchboard with two load-breaking switches as Fig. 5-1 in centre (Johnson and Phillips, Ltd.).

As to (*a*), it is possible when using a design incorporating tripping fuses, by virtue of the tripping facilities on the handle gear, to arrange that a shunt trip coil shall also cause tripping and the usual forms of relays can therefore be provided. This involves current transformers, and possibly voltage transformers if directional protection is desired, and all this leads to considerable expense.

As to (*b*), a design recently offered is shown in Fig. 5-1, where it will be seen that the unit is arranged with compound filled busbars. This unit can be lined up with and form an integral part of a compound filled switchboard, an example of which is noted in Fig. 5-2. Here there are five full circuit-breaker equipments and two load-breaking switches. Of these, that on the left hand incorporates fuses, while that on the right hand is a straight load-breaking switch acting as a bus-section.

A feature of the design is that if at some later date it becomes necessary to change over from the load-breaking switch and fuses to a circuit-breaker equipment, this can be readily achieved as the housings and cabling arrangements are made to be interchangeable.

Another application where an equipment of this type might usefully be used is that of a simple stub-end feeder which is fed from a board similar to Fig. 5-2. In this case, provision may be required for earthing the cable and for testing. These facilities are provided as will be noted from Fig. 5-1.

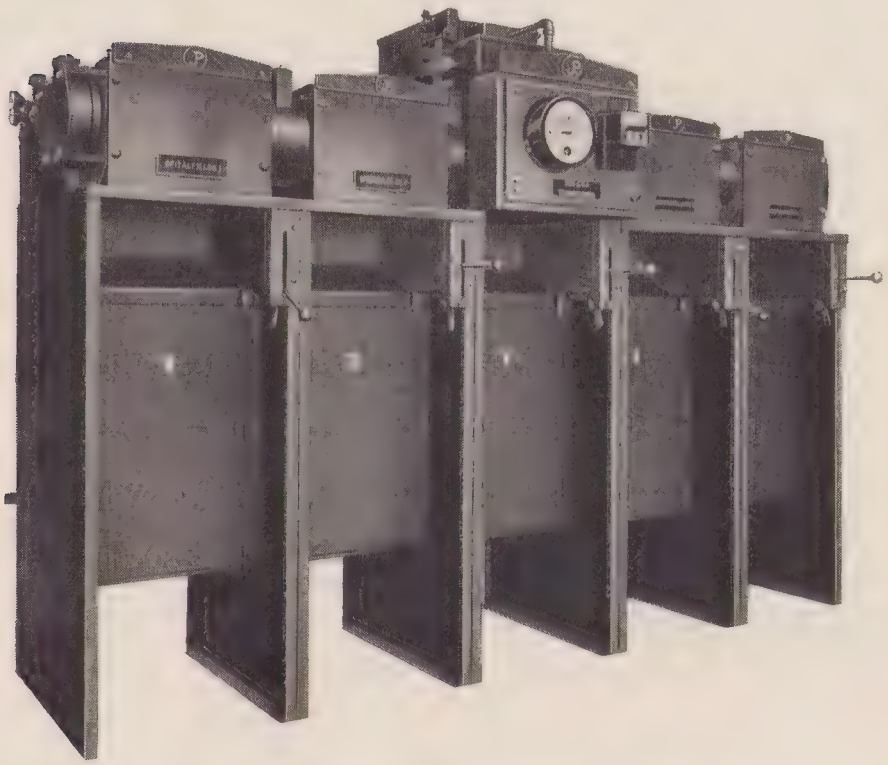


FIG. 5-3.—*Switchboard of Load-Breaking Switches with tripping fuses (Johnson and Phillips, Ltd.).*

In this latter illustration, too, the possibility of accommodating current transformers is indicated, these being mounted in the cupboard housing the fuses.

Full interlocks are provided, including the door giving access to the fuses, which can only be opened when the switch is open.

Where the conditions do not demand a circuit-breaker on any equipment, any number of load-breaking switches can be lined up to form a complete switchboard and an example of this is shown in Fig. 5-3. Here a 500 kVA transformer circuit is controlled by the centre equipment and

from the busbars four simple feeders are taken away. It is noted that on the transformer circuit, metering has been provided, the voltage transformer (plug-in type) being mounted on top of the unit.

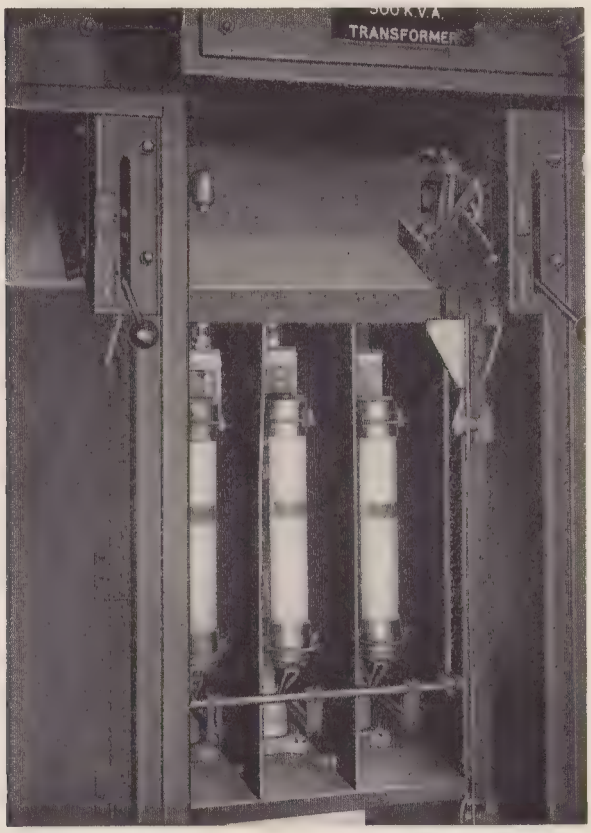


FIG. 5-4.—*Fuse Cabinet in Load-Breaking Switch (Johnson and Phillips, Ltd.).*

Fig. 5-4 shows the arrangement of the fuse compartment with the tripping bar and the link to the operating handle.

It has been stated that the economical value of this type of equipment is at the higher values of short-circuit. Table 1 gives an indication of the breaking capacity of available fuses.

TABLE 1

Rated Voltage kV	Current Rating Range of Fuse Amps.	Breaking Capacity Three Phase MVA
3·3	1—50	250
3·3	51—300	150
6·6	1—50	350
6·6	51—200	250
11·0	1—30	400
11·0	31—100	300
11·0	101—200	250

The need for intertripping envisaged by Wood in his paper can readily be achieved. A shunt trip on the h.v. load-breaking switch is energised by the opening of the circuit-breaker, for example, on the l.v. side of a power transformer. A similar arrangement is applied to rectifier circuits where the opening of the d.c. circuit-breaker initiates the opening of the h.v. switch.

The simplicity of the load-breaking switch is made possible only by reason of the cut-off effect of the fuse. It is well known that this occurs in some degree in all h.r.c. fuses of the powder filled cartridge type and all apparatus associated with the circuit in which a fuse appears has to withstand the electromagnetic and other forces due to the cut-off value of current instead of the full short-circuit value of current which could appear had no fuses been fitted, *i.e.*, the prospective current. The importance of this may be appreciated by noting the figures in Table 2 obtained from short-circuit tests.

TABLE 2

Fuse Rating Amps.	Prospective Current r.m.s. Amps.	Cut-off Current Amps.
3	14,000	450
10	14,000	1,870
100	14,000	7,900
150	14,000	8,600
200	14,000	12,000

Figs. 5-5 and 5-6 illustrate an example of 3·3 kV oil circuit-breaker units with back-up tripping fuses in air, providing breaking capacities up to 250 MVA.

BIBLIOGRAPHY

"CITY DISTRIBUTION IN LOW-VOLTAGE NETWORKS," B. Wood, "Journal I.E.E.," 1942, Vol. 89, Part II, p. 400.

"A HIGH-VOLTAGE HIGH-RUPTURING CAPACITY FUSE AND ITS EFFECT ON PROTECTION TECHNIQUE," K. Dannenberg and Professor W. J. John, "Journal I.E.E.," 1942, Vol. 89, Part II, p. 565.

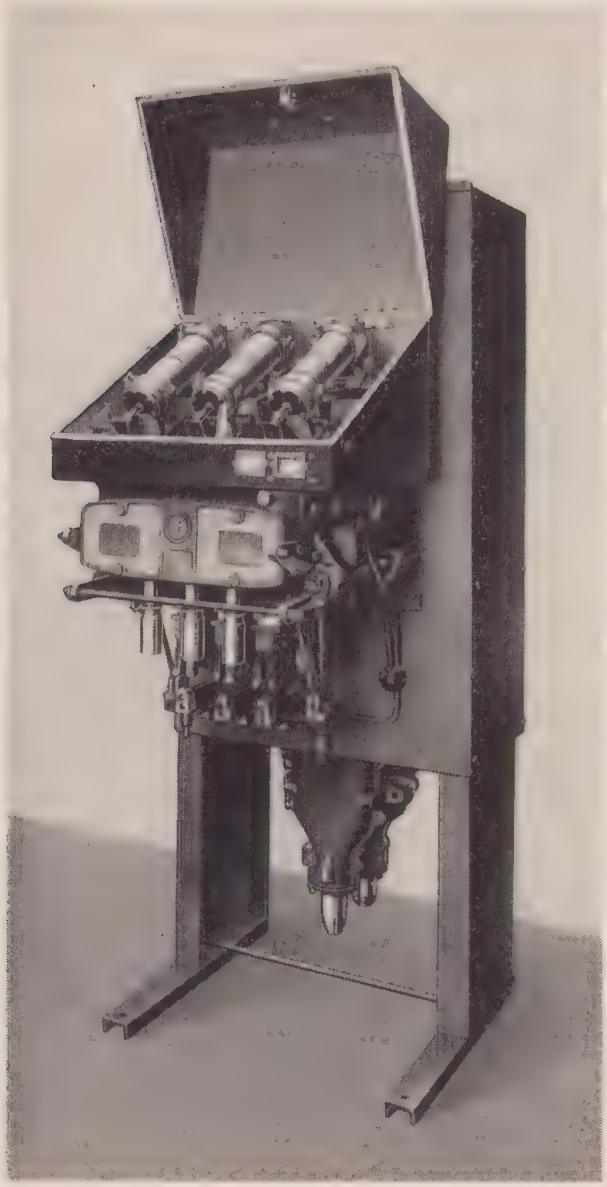


FIG. 5-5.—3·3 *kV Oil Circuit-Breaker Unit with tripping fuses. Fuse lid raised to show fuses. Breaker tank also removed (J. & P., Ltd.).*

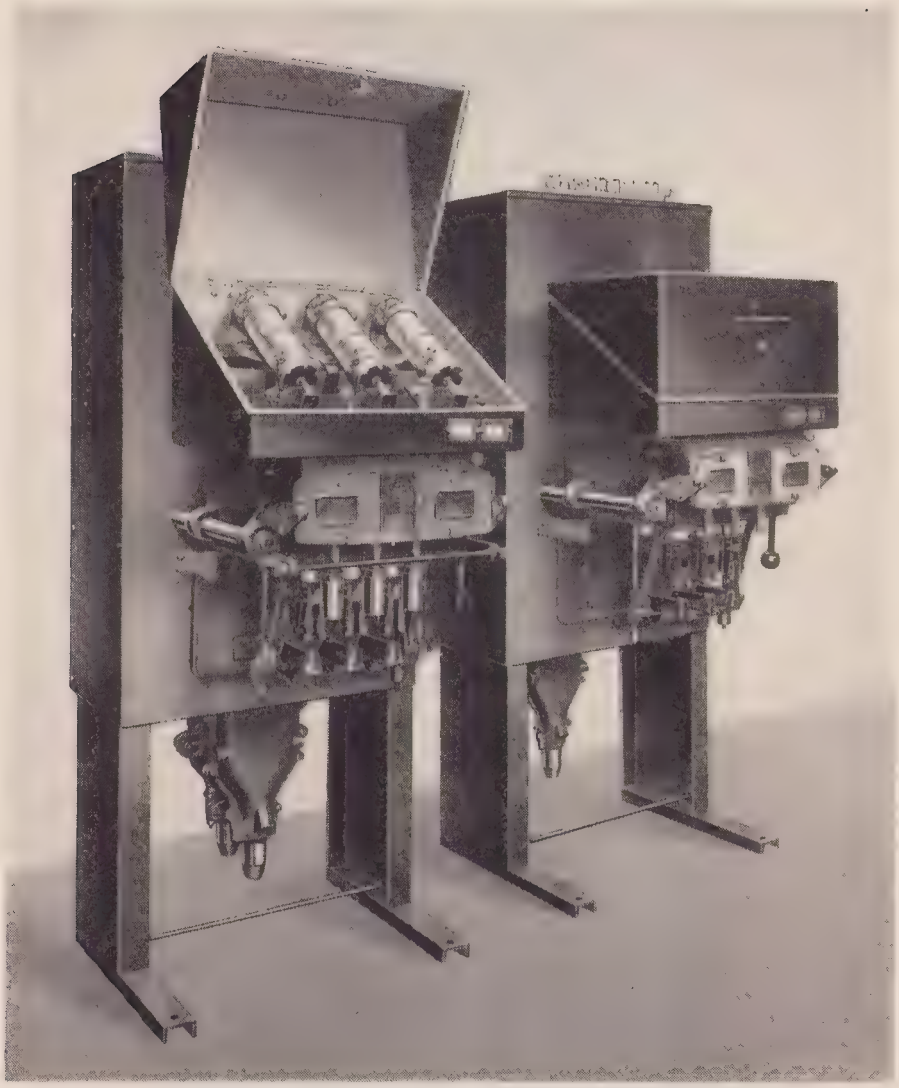


FIG. 5-6.—3·3 *kV Oil Circuit-Breaker Units with tripping fuses. Breaker tanks removed for illustration (J. & P., Ltd.).*

CHAPTER VI

LOW VOLTAGE ALTERNATING CURRENT SWITCHGEAR

THERE is available a variety of switchgear designs suitable for low-voltage systems, *i.e.*, for systems where the voltage does not exceed 650 volts. Some of these, as will be shown, follow those designs used on h.v. systems, while others are peculiar to l.v. In general, the former are used for the heavier current ratings, *e.g.*, above 1,000 amperes, where oil circuit-breakers are demanded. Those peculiar to l.v. are generally for the lower current

FIG. 6-1.—*Flat Back a.c. l.v. Switchboard with circuit-breakers in main circuits and open switches and fuses for distribution (J. & P., Ltd.).*

ratings except that recent development in air-break designs of circuit-breakers, has produced gear incorporating these up to very high current values.

The majority of applications are those which arise in industrial situations. The rapid increase in industrial demand, an increase considerably accentuated

by the demands of war production, has led to a situation where large blocks of power are supplied at low voltage, resulting in an increase in the fault powers which can arise, and this has led to a need for circuit-breakers having higher breaking capacities than hitherto. It is in this direction that the l.v. air break design has made great strides and has introduced new types of gear incorporating this type of circuit-breaker.

The simplest form of l.v. switchboard comprises a panel construction of which two examples are shown in Figs. 6-1 and 6-2, the former having low breaking capacity circuit-breakers for the main circuits and open switches (knife type) and porcelain handle fuses for distribution.

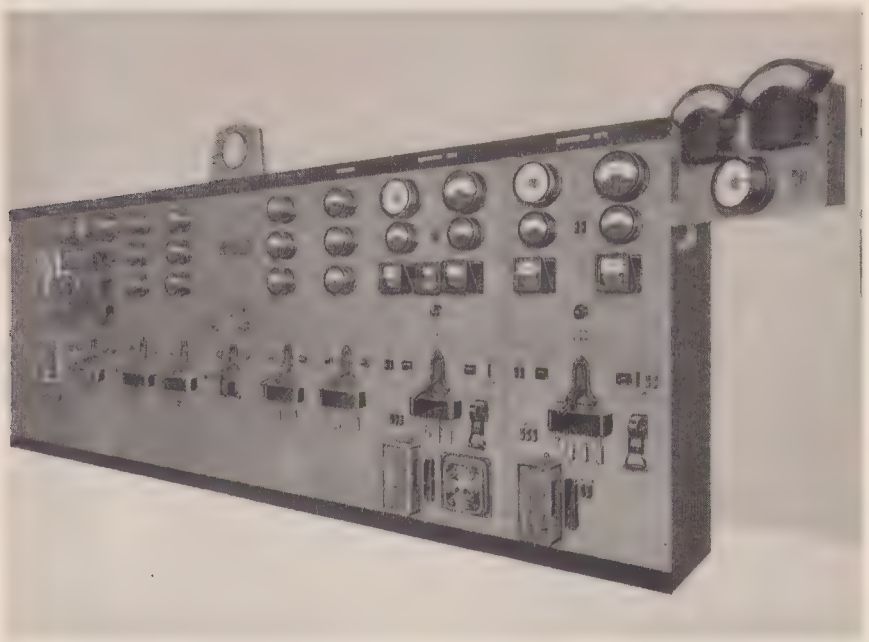


FIG. 6-2.—*Flat Back a.c. l.v. Switchboard for Generating Station. Note that upper panels are hinged to give access to wiring, etc. (J. & P., Ltd.).*

The board shown in Fig. 6-2 controls two small generators and a number of power and lighting circuits, with provision for an emergency supply from a local authority.

This switchboard is typical of many supplied for small private generating stations, the example being for a large hospital.

For installations where high powers are involved, typically in large industrial installations where supply is taken at high-voltage from the local authority, the cubicle type of switchboard is a popular choice. Examples of this are shown in Figs. 6-3 and 6-4. This type has one advantage over

other types in that the cubicles, being built to measure, can be arranged to accommodate any specified equipment. This is often a disadvantage with unit types where the standard dimensions permit only a limited equipment to be mounted. If maintenance is to be given, it is important that ample means of access be provided and wherever possible it should be made both back and front. If back access only is possible, the internal arrangement of equipment must be closely studied.

Cubicle type switchgear of the type illustrated can be of the interlocked or non-interlocked type. In the former, the doors, isolating switches, and

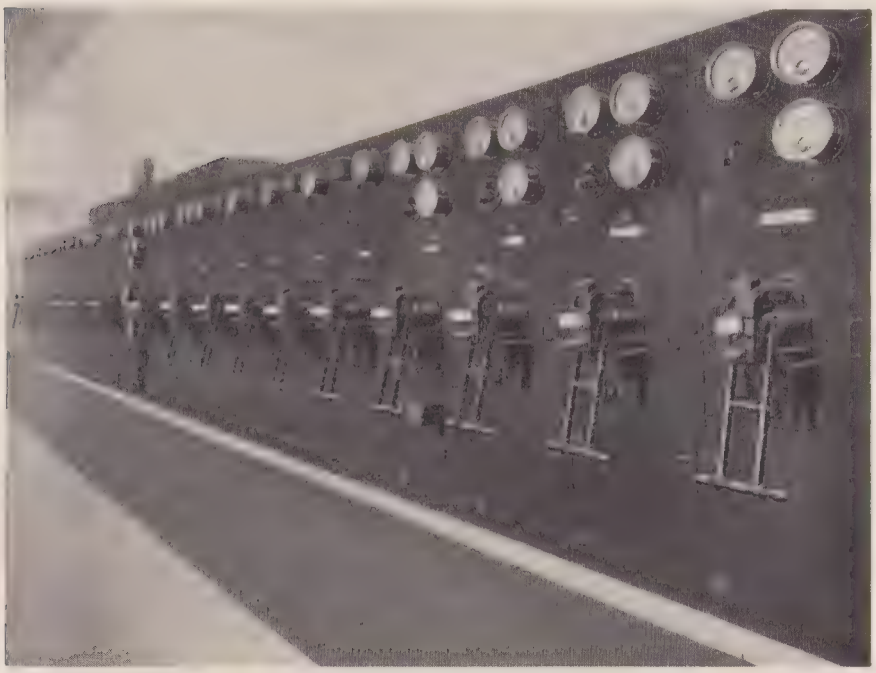


FIG. 6-3.—*Cubicle Type a.c. l.v. Switchboard with breakers of high breaking capacity. Note long handles to provide easy closing operation (J. & P., Ltd.).*

the circuit-breaker are so interlocked that access can only be obtained after the circuit-breaker and isolators are open and the sequence is such that the breaker must be opened before the isolators. Such interlocks add considerably to the cost and may under certain circumstances give a false sense of security. It must rest with the user to decide whether or not they are provided, his decision taking into account the degree of skill and responsibility of those he will employ as operators. If interlocks are fitted, it is preferable that they be mechanical and not electrical. The latter demands a separate source of electrical supply which may fail.

Two further examples of the cubicle type switchboard are given in Figs. 6-5 and 6-6.

Difficulty of access to a cubicle housing a very heavy current circuit-breaker with its mass of copper conductors leading in and away has led to the development of a type where the circuit-breaker is mounted on a wheeled carriage which can be removed from the cubicle for maintenance and adjustment. An example of this is shown in Figs. 6-7 and 6-8. The usual isolating switches are supplied for isolating the circuit-breaker, these being in the fixed cubicle, but in addition two three-phase sets of clamped links are provided at the circuit-breaker terminals, these links taking the form of

FIG. 6-4.—*View of Industrial Substation with l.v. Cubicle Switchboard on left and at far end, h.v. Switchgear on right—cubicle type incoming from supply authority and truck type for consumer—Capacitors in centre of room, with tripping battery cabinets beyond.* 10,000 *kVA of transformers connected, these being in bays outside in units of* 1,000 *kVA. Fire fighting* (CO_2) *equipment installed (Johnson and Phillips, Ltd.).*

jaw clamping devices. By this means, the need to unbolt a number of heavy connecting joints is avoided and at the same time there is no disturbance to the conductors. The alternative is to mount the circuit-breaker in a truck type cubicle similar to those used in h.v. work, but this involves the use of plug and socket contacts, a feature to be avoided wherever possible when dealing with currents of the magnitude of 2,000/3,000 amperes. On the other hand truck type cubicles are available for current ratings of 1,200/1,600 amperes.

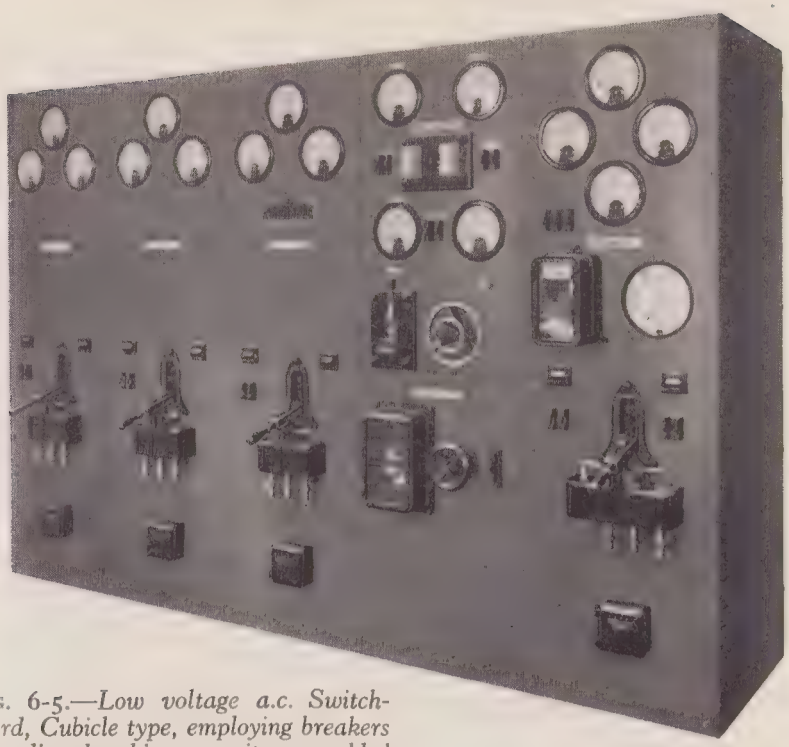


FIG. 6-5.—*Low voltage a.c. Switchboard, Cubicle type, employing breakers of medium breaking capacity, assembled in the South African works of J. & P.*

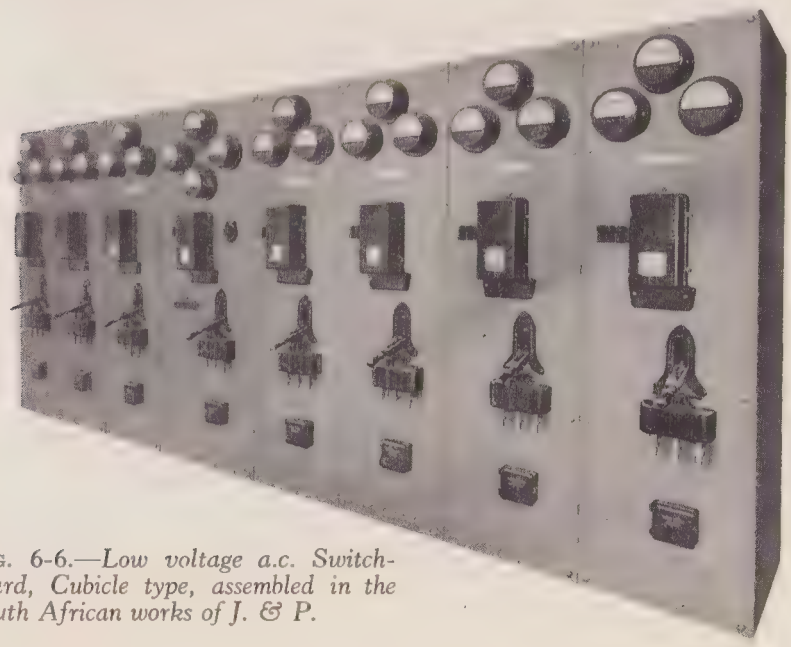


FIG. 6-6.—*Low voltage a.c. Switchboard, Cubicle type, assembled in the South African works of J. & P.*

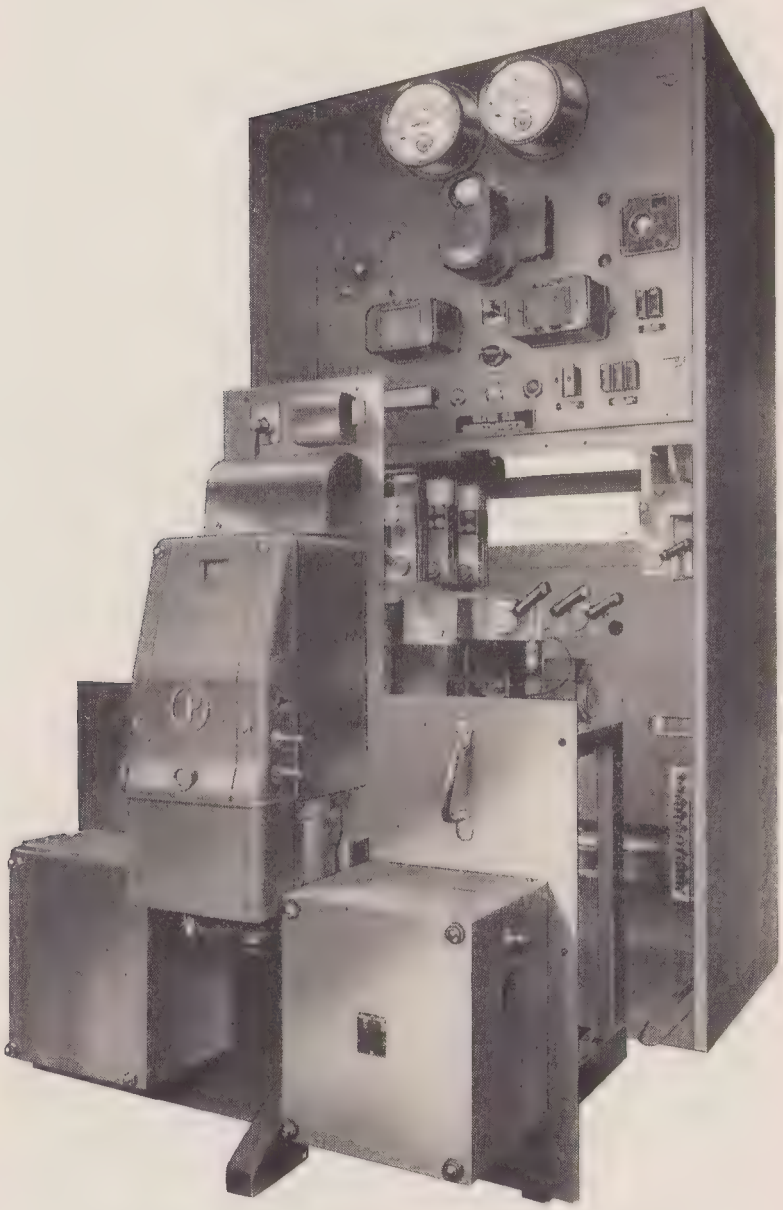


FIG. 6-7.—3,000 *amp. Breaker on removable truck (J. & P., Ltd.).*

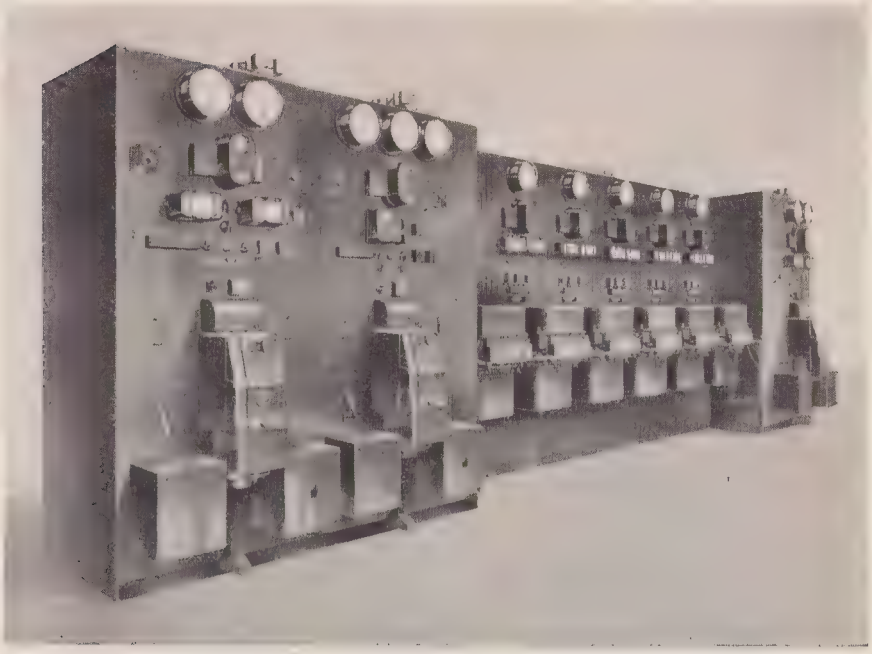


FIG. 6-8.—*Low voltage a.c. Switchboard with heavy current circuit-breakers on wheeled carriages as Fig. 6-7 (J. & P., Ltd.).*

FIG. 6-9.—*Low voltage Switchboard in single tier formation (J. & P., Ltd.)*

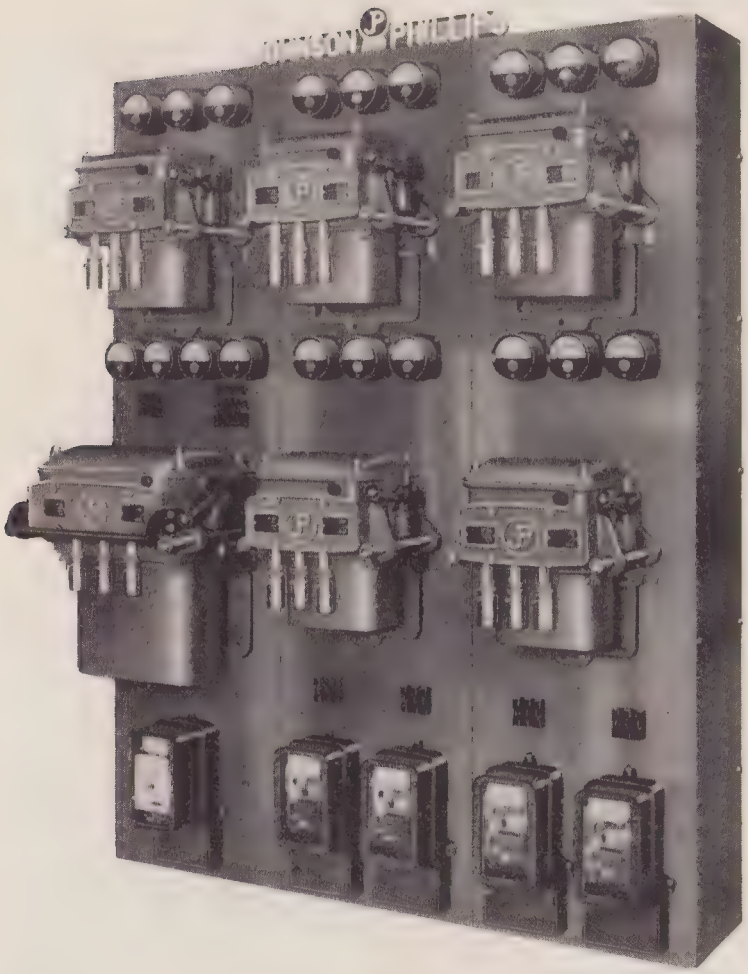


FIG. 6-10.—*Low voltage a.c. Switchboard with draw-out units in double tier formation (J. & P., Ltd.).*

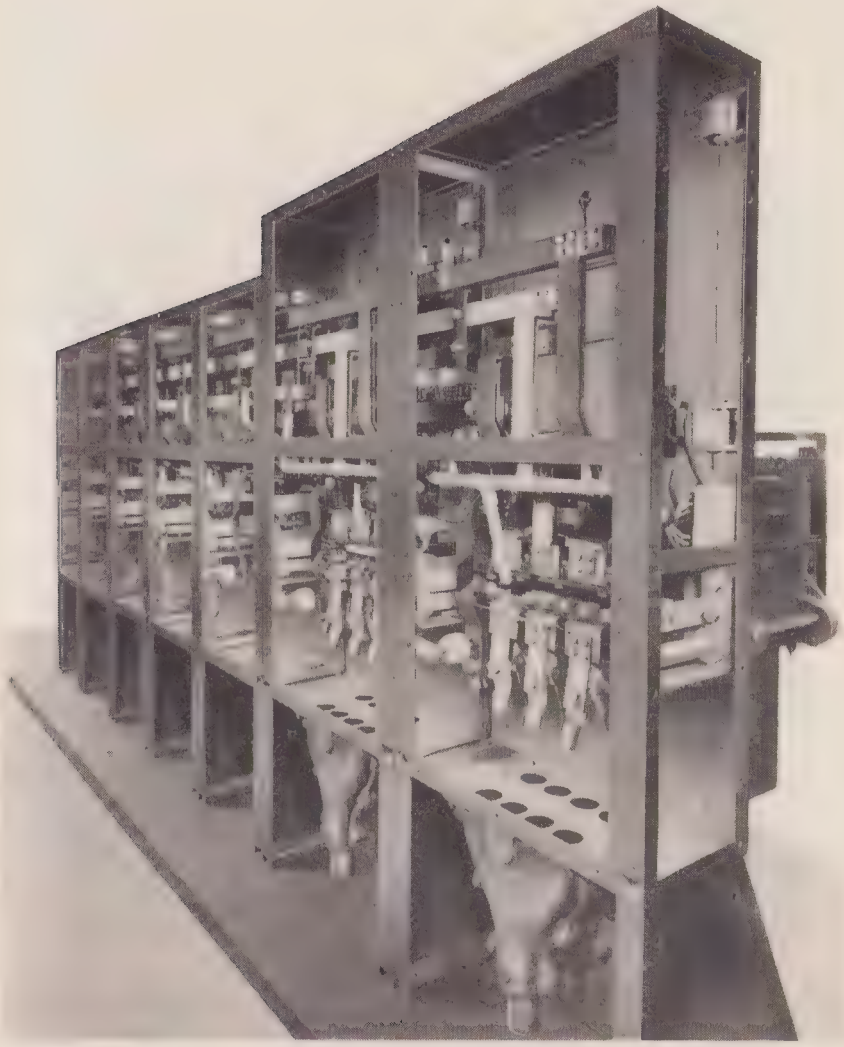


FIG. 6-11.—*Back view of low-voltage ironclad switchboard, showing busbars supported to withstand short-circuit forces of high value, e.g., 30 MVA at 400 volts. Cabling arrangements clearly shown (J. & P., Ltd.).*

By far the most popular of industrial switchboards is the ironclad type. The total enclosure in earthed metal of this type makes it a safe form for installations where operators may not be as skilled or so technical as in larger installations. It can readily incorporate all the essential safety interlocks and yet be quite economical in first cost.

Two examples of switchboards of this type are shown in Figs. 6-9 and 6-10, the former being arranged as a single tier construction, the latter

FIG. 6-12.—*Low voltage a.c. Switchboard with cubicle type incoming and drawout industrial units and switch-fuses for distribution (J. & P., Ltd.).*

having circuit-breakers in two tiers. This double tier arrangement permits a considerable saving in substation space. The circuit-breakers in the two illustrations are of the draw-out type, providing double isolation of the circuit-breaker.

This type is to be favoured for all switchboard work as it makes maintenance on individual circuit-breakers a simple matter with no element of danger. Rear access is usual with this type of board and Fig. 6-11 illustrates the rear view of such a switchboard with the back covers removed.

Where oil circuit-breakers are not justified for every circuit, ironclad switch-fuses or fuse-switches can readily be lined up with the ironclad circuit-breakers. An example of such an arrangement is shown in Fig. 6-12.

In the ironclad circuit-breakers so far illustrated, the contact system is based on that used in h.v. design for plain break. Fig. 6-13 is typical, from which it is noted that wedge and finger contacts are used, the features of which are discussed in Chapter VIII. In general, the upper limit of current carrying capacity for this class of breaker is 1,200 amps. at not more than 650 volts.

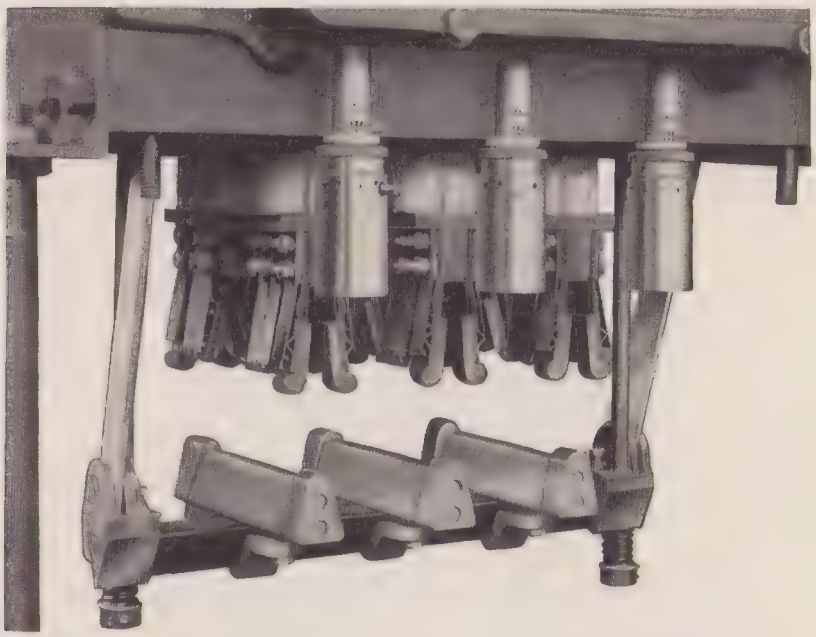


FIG. 6-13.—*Showing the contact system used in the industrial circuit breaker. This follows the design used in high-voltage work.*

Sub-distribution at low-voltage is often controlled either from switch-boards comprising fuse-switches, a typical unit being shown in Fig. 6-14 or from what is described as a "Skeleton" type board employing open fuse-switch units. An example of this for power supply is shown in Fig. 6-15 while a similar board enclosed in a cubicle is shown in Fig. 6-16, this type being specially developed for shop distribution in factories where operatives are in and about during their work. It is very economical and takes up little room in view of the vertical arrangement of the phases. In the type shown a design of fuse-switch is used which enables a fuse to be changed safely by removing the blade and fuse from its contacts. This is shown in Fig. 6-17.

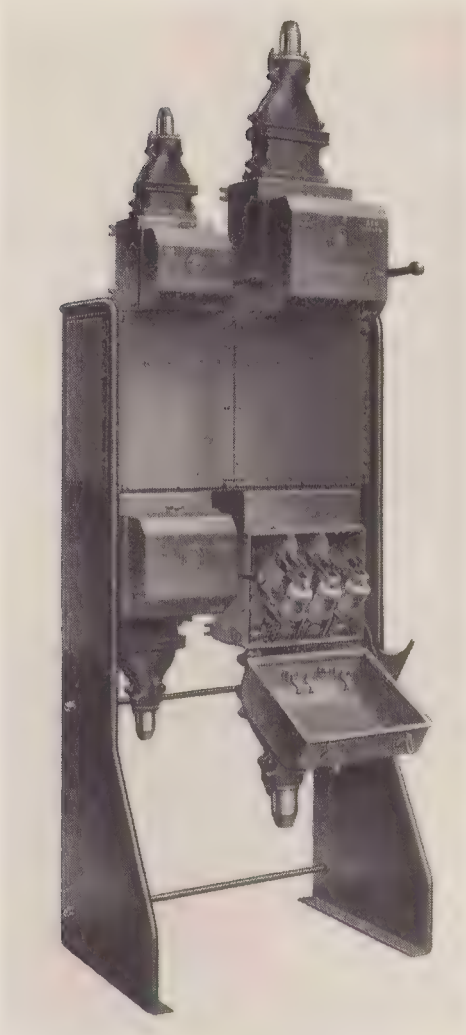


FIG. 6-14.—*Typical switchboard using fuse-switches (J. & P., Ltd.).*

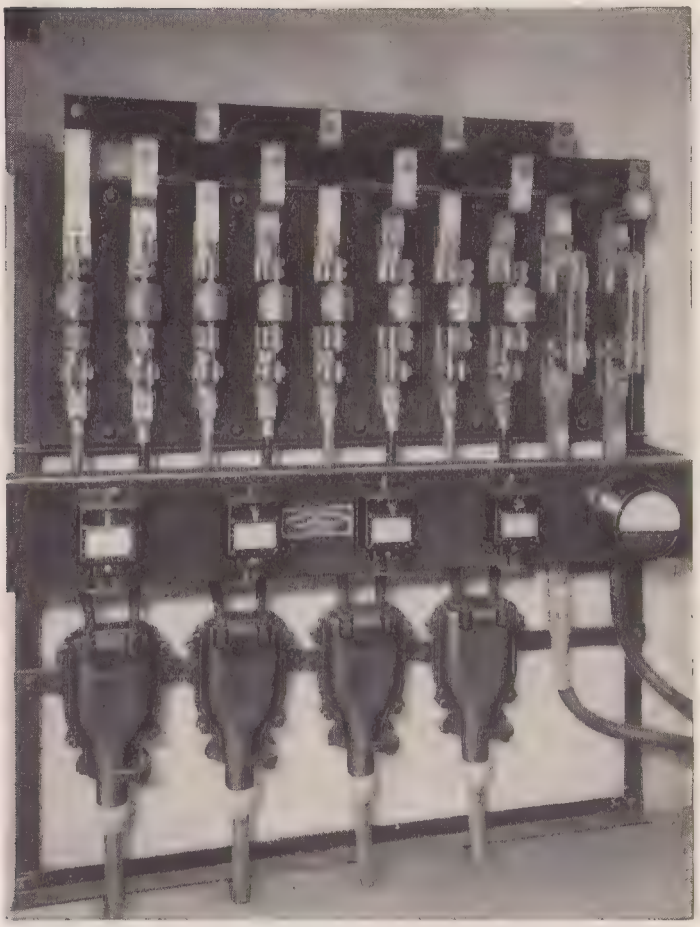


FIG. 6-15.—*" Skeleton " Type Distribution Board employing fuse-switch units as* FIG. 6-17 *(J. & P., Ltd.).*

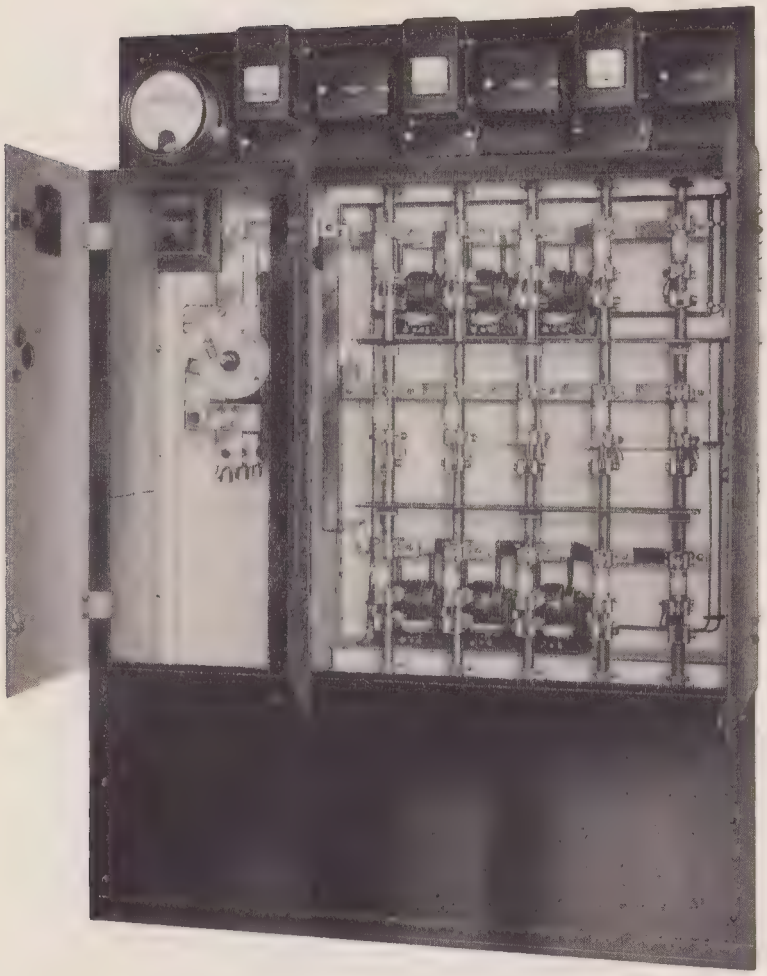
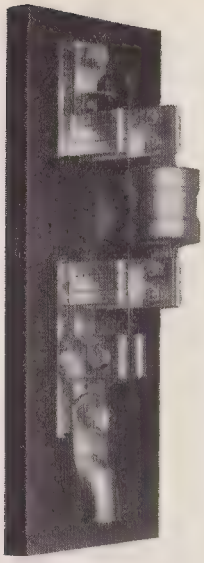


FIG. 6-16.—*Another example of "Skeleton" Type Distribution Board, with cubicle enclosure and metering equipment (J. & P., Ltd.).*



(*a*)—"*J. & P*" *Combined Fuse-switch in closed position.*

(*b*)—*As* (*a*), *but Fuse-switch being opened with short insulated handle.*

(*c*)—*As* (*a*), *unit fully open being withdrawn for cartridge renewal.*

FIG. 6-17.

The most recent development in l.v. switchgear is that using air-break circuit-breakers. The tendency towards eliminating all fire risks due to oil has urged this development forward and there are now several designs available.

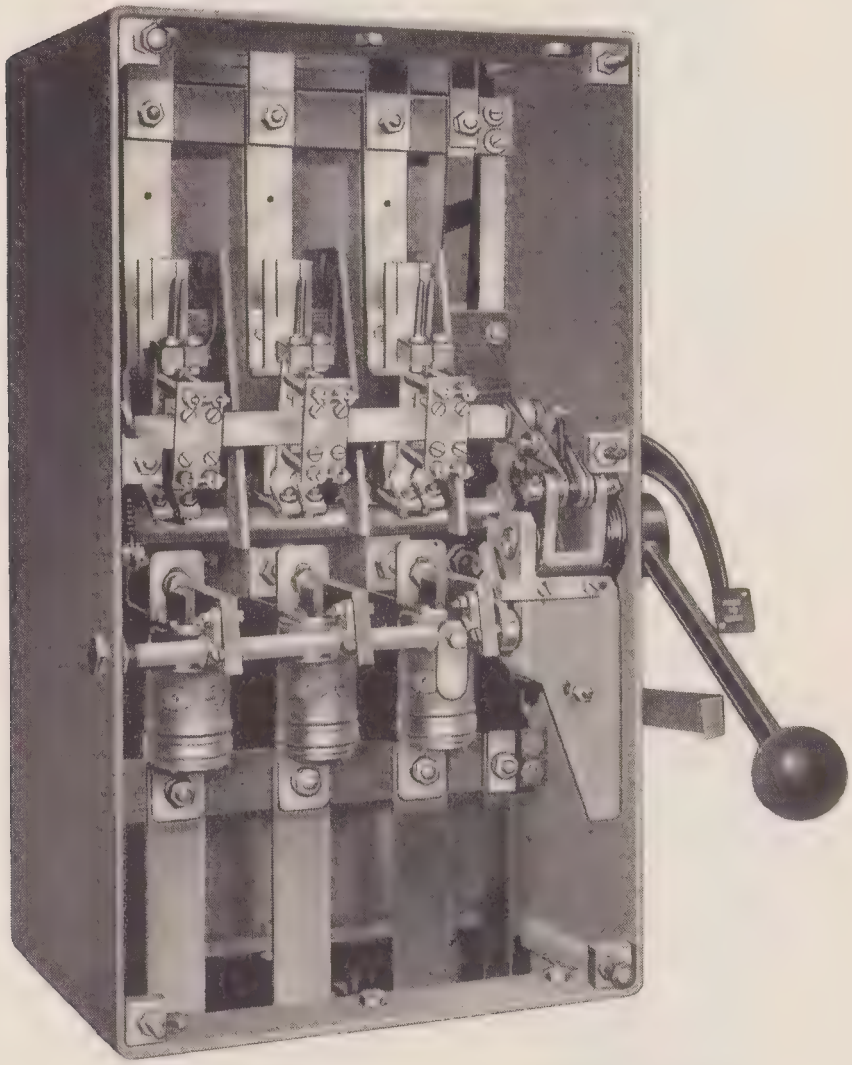


FIG. 6-18.—*Air-Break Circuit-Breaker with tripping fuses, cover removed (J. & P., Ltd.).*

In one design, of which more detail will be given in Chapter XI, an air-circuit-breaker is used in conjunction with tripping fuses. An example of such a circuit-breaker is given in Fig. 6-18.

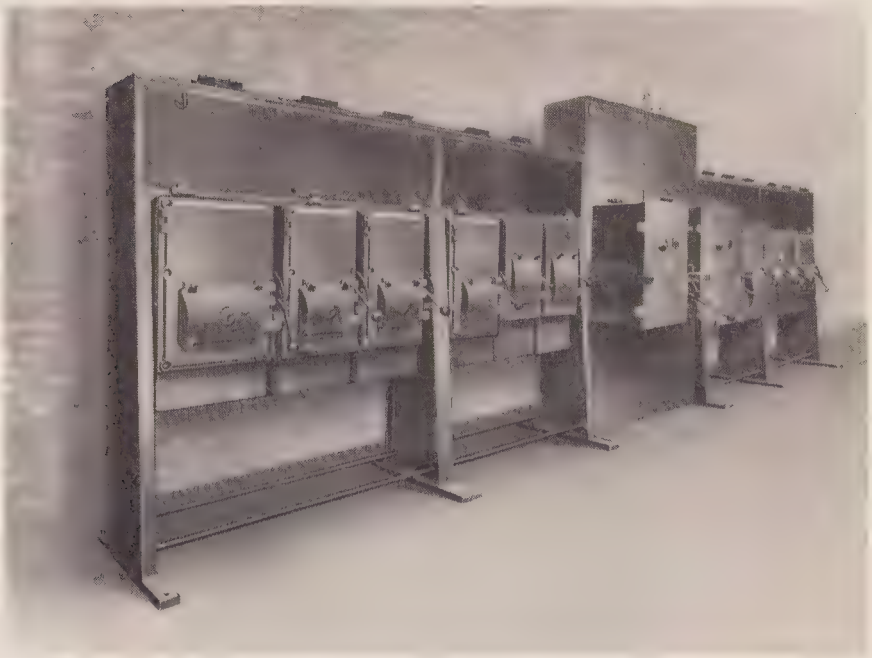


FIG. 6-19.—*Low voltage Switchboard of fixed and draw-out type air circuit-breakers (J. & P., Ltd.).*

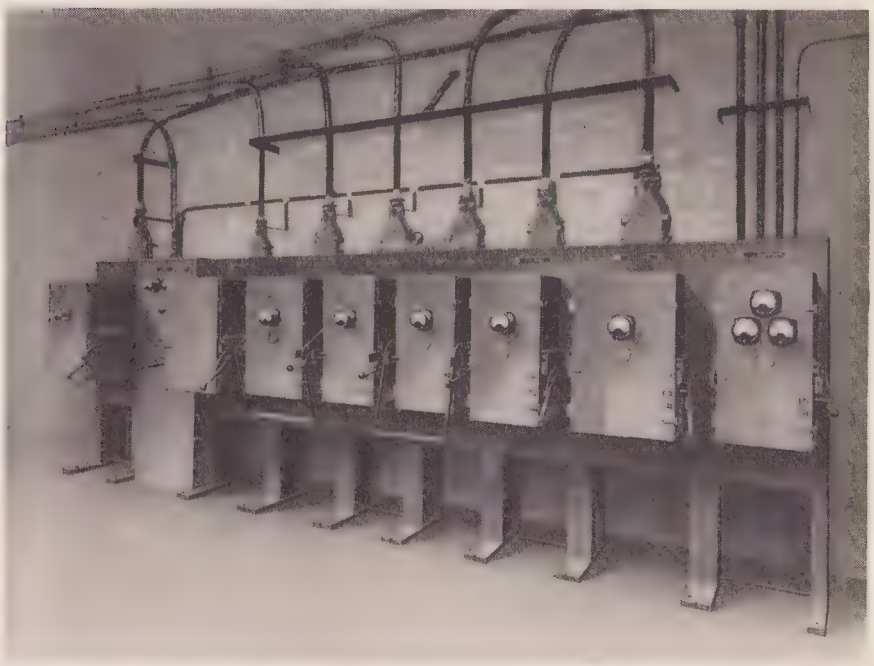


FIG. 6-20.—*Low voltage Switchboard of Draw-out type Air Circuit-Breakers (J. & P., Ltd.).*

A range of gear up to 800 amps. is available in this design and the circuit-breakers can be of the fixed or draw-out types. A switchboard incorporating the former is shown in Fig. 6-19, while a board of draw-out circuit-breakers is illustrated in Fig. 6-20.

In addition to the use of fuses, this type can include all the usual forms of excess or fault current tripping, *e.g.*, overload trips, earth leakage, shunt trips, etc.

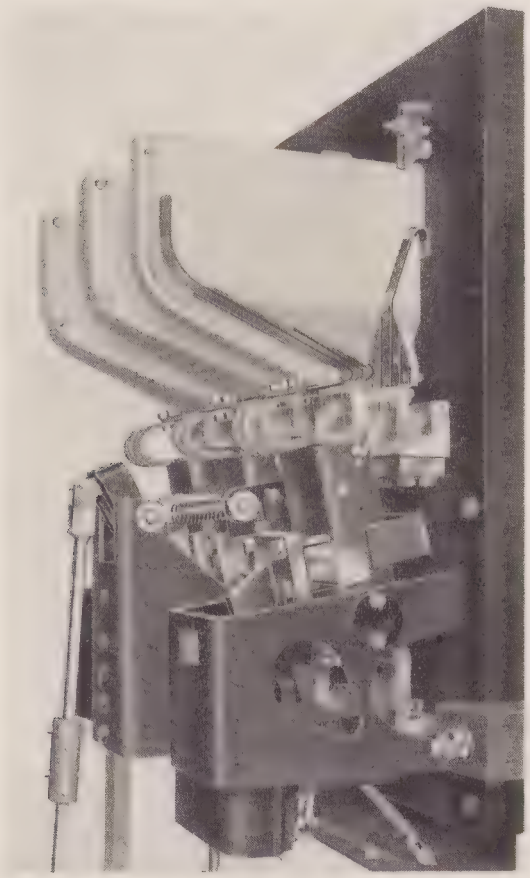


FIG. 6-21.—*Air-Break Circuit-Breaker with part of chute removed (The British Thomson-Houston Co., Ltd.).*

In another development, the range of air circuit-breakers is taken up to 3,000 amperes. Two well known designs are those of The British Thomson-Houston Co., Ltd. and The English Electric Co., Ltd. The required breaking capacity in these designs is obtained without the use of fuses. In the B.T.H. design shown in Figs. 6-21 and 6-22 a special arrangement of contacts is

used, together with an arc chute. This chute is not essential to arc rupture but is employed to prevent the arc wandering to earth or between phases. Fig. 6-23 illustrates the form of contact employed, which embodies the following requirements :—

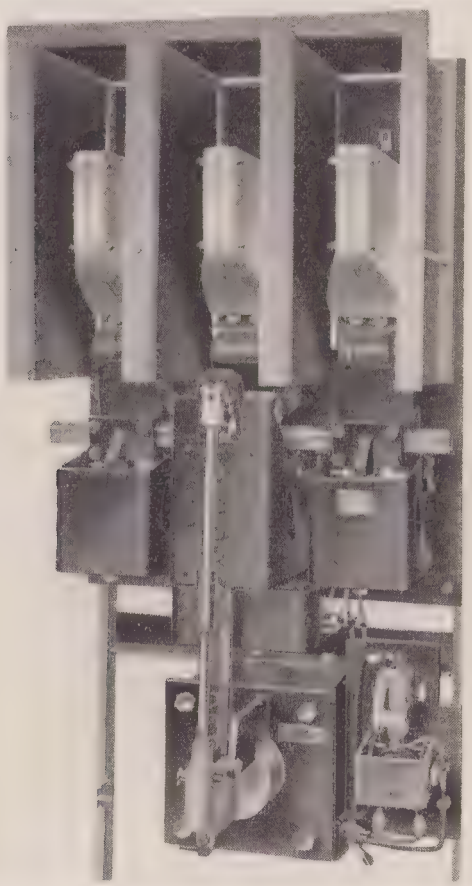


FIG. 6-22.—*Air-Break Circuit-Breaker showing chutes and dividing barriers* (*The British Thomson-Houston Co., Ltd.*).

(*a*) The minimum magnetic field is applied capable of keeping the arc continuously moving up the chute and to ensure that it is extended sufficiently to extinguish at the first or second current zero.

(*b*) The distance between the plates of the chute is small enough to prevent the arc unduly lengthening by zig-zagging and yet is large

enough to ensure that the free movement of the arc is not impeded by strangulation. The distance between plates is equal to the diameter of the arc for a given fault current.

(*c*) The horns are of such a length that the cathode spots formed at their ends are far enough apart not to cause restriking.

No magnetic blow-out is employed as the same effect is achieved by the loop formed by the arc and its leads. For currents between 2,000 and 37,000 amperes r.m.s. the blow-out effect described is more than sufficient to force the arc into the chute. At lower currents, tests proved that the arc would

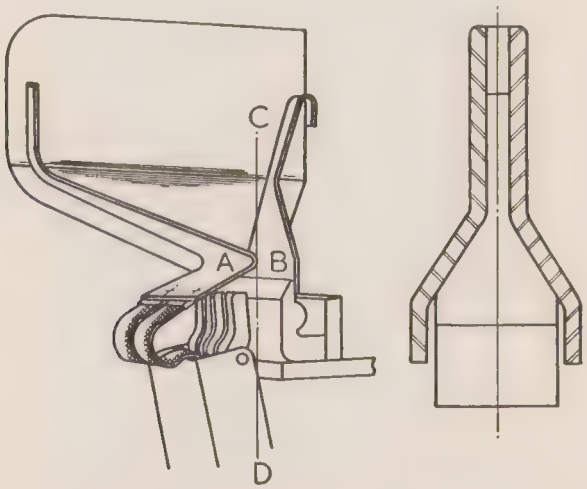


FIG. 6-23.—*Contacts, Horn and Chute Structure for B.T.H. Air Circuit-Breaker (The British Thomson-Houston Co., Ltd.).*

tend to burn indefinitely across the points A-B in Fig. 6-23. This undesirable feature is overcome by the simple expedient of splitting the horn at A into five parts which has the effect of increasing the magnetic field five times. The horns are made of steel which again strengthens the field at the root of the arc.

The U-shaped phase barriers shown in Fig. 6-22 act as expansion chambers for incandescent air and metal vapours ejected from the top of the arc chutes, and direct the gases down the sides of the chutes, cooling them before they reach earthed metal or mingle with the gases from a neighbouring phase.

Isolation can be provided by arranging the circuit-breaker and its panel to be hinged and swing forward. Operation of the circuit-breaker is by hand or solenoid mechanism. The rating is 25 MVA at 400 volts and 35 MVA at 660 volts. Fig. 6-24 shows a complete cubicle arrangement with the means for isolating as described.

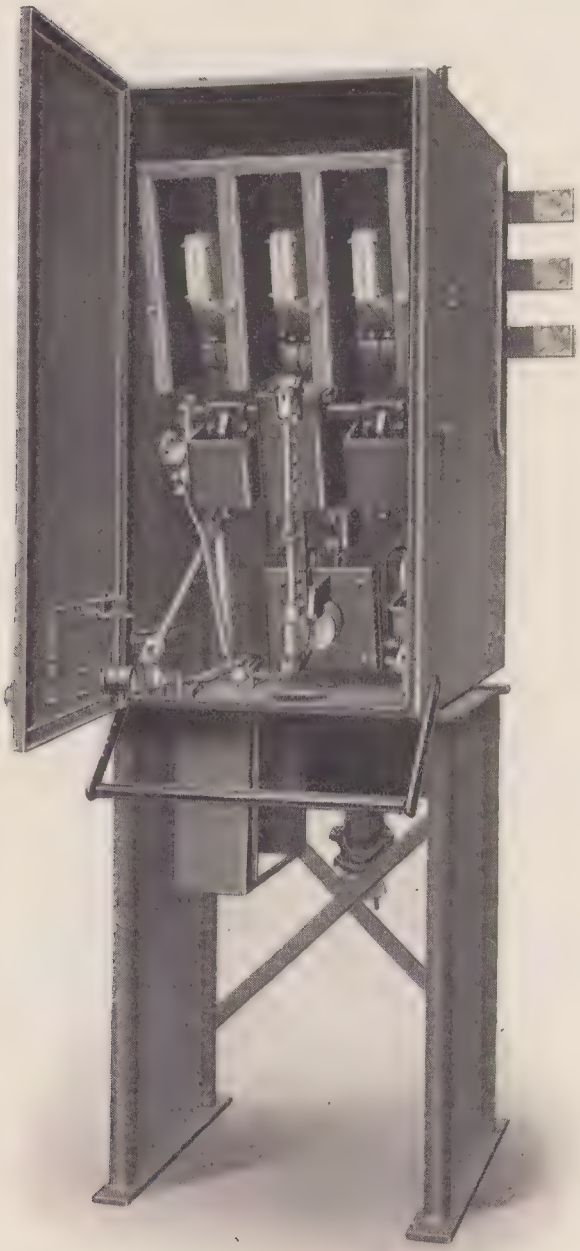


FIG. 6-24.—*Solenoid Operated Air-Break Circuit-Breaker, in cubicle with isolating feature (The British Thomson-Houston Co., Ltd.).*

In the English Electric type, an arcing chamber of special design is used to surround the contacts, the chamber being described as a *de-ionising arc splitter*. Figs. 6-25 and 6-26 illustrate this chamber, from which it is noted that there are a number of insulating plates of non-gas-forming material with V-shaped slots.

FIG. 6-25.—*Arcing Chamber, bottom view, showing arrangement of insulating plates (The English Electric Co., Ltd.).*

They are spaced at intervals of approximately 3/16 inch and at right angles to the arc. The slots are narrower at the upper end than at the lower, where space is required for the movement of the arc tips and contact arm. A correct balance of arc constriction and magnetic control is achieved

by the arc chamber, the former by the shape of the plates and the spacing, reducing the arc section sufficiently to make magnetic control effective. Magnetic control is achieved by the inclusion of a series of iron plates, equal in number and spacing to the insulating plates.

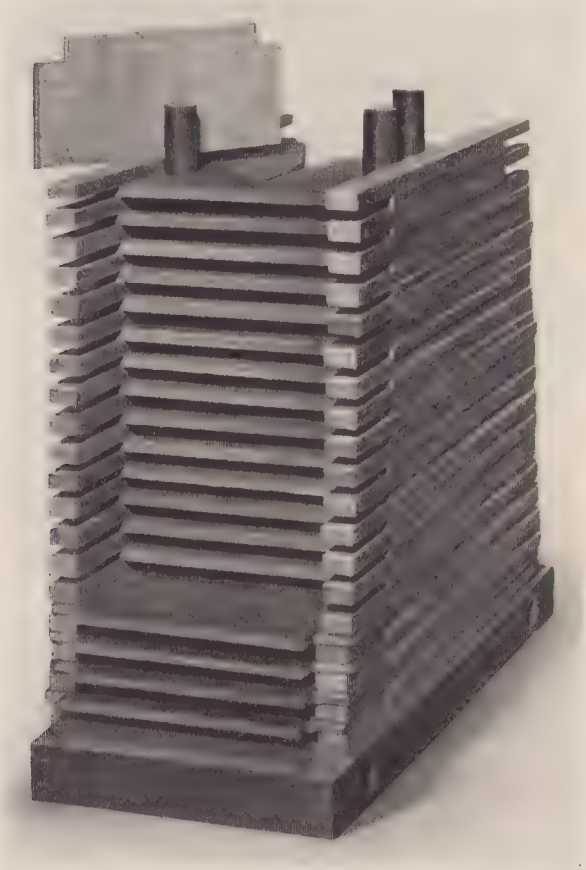


FIG. 6-26.—*Arcing Chamber, top view, showing location of iron plates (The English Electric Co., Ltd.).*

The contact arrangement is described as " three-stage " and the sequence is shown in Fig. 6-27.

As in the B.T.H. design, isolation can be provided by hingeing the panel forward, and operation is by hand or solenoid. A typical circuit-breaker is illustrated in Fig. 6-28.

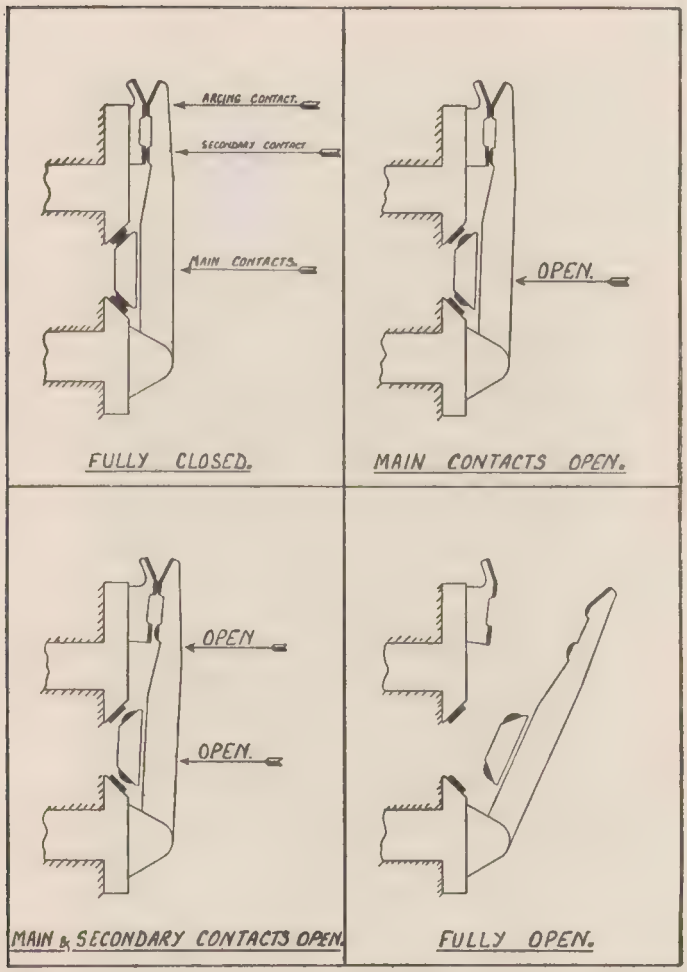


FIG. 6-27.—*Contact opening sequence of 400 volt Air-break Circuit-Breaker (The English Electric Co., Ltd.).*

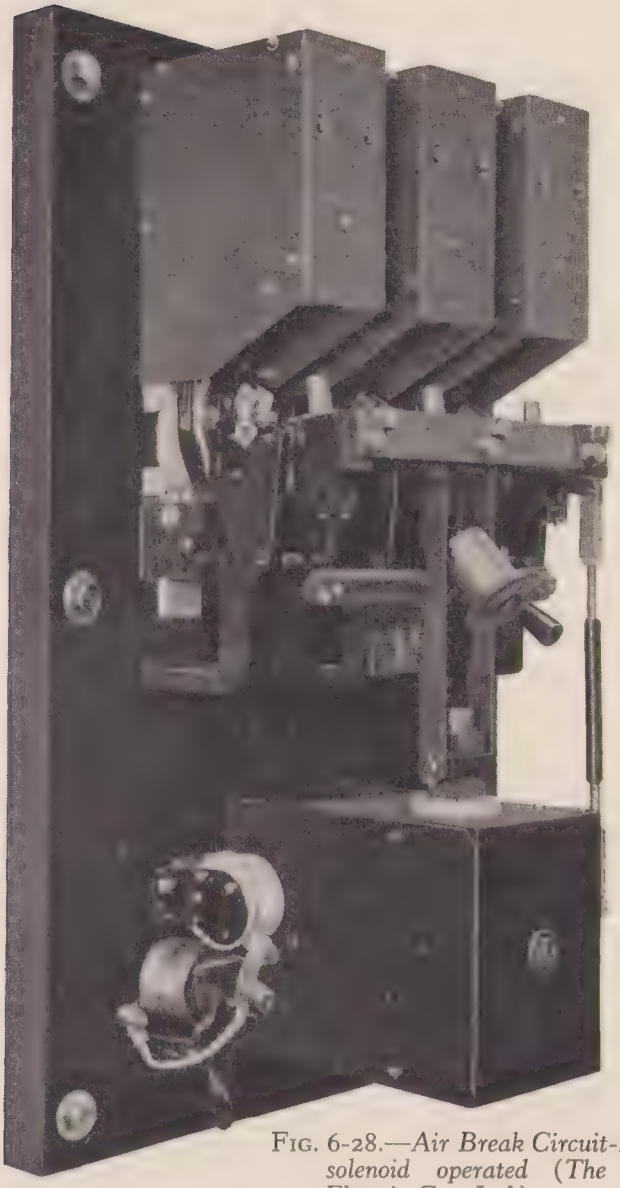


FIG. 6-28.—*Air Break Circuit-Breaker, solenoid operated (The English Electric Co., Ltd.).*

BIBLIOGRAPHY

" Oil-less Metalclad Switchgear for Medium Voltage Alternating Current Circuits up to 660 Volts," H. E. Cox and L. Drucquer, " Journal I.E.E.," Vol. 87, Pg. 527.

" New Developments in Air-Break Circuit-Breakers," A. R. Blandford, " English Electric Journal," April, 1940.

Switchgear Handbook, W. A. Coates and H. Pearce, Vol. II (Pitman and Sons).

CHAPTER VII

OUTLINE OF CIRCUIT-INTERRUPTION THEORY

During the years since the first world war, considerable research work has been carried out on the problem of circuit interruption, with the result that it is now possible to design an interrupting device which, within certain limits, can confidently be submitted to proving tests with a knowledge that the basis of the design is free of guesswork. As the majority of interrupting problems, particularly at the higher powers, are concerned with alternating current, it is natural that research should be directed towards this aspect rather than to direct current. In the a.c. circuit, interruption is fundamentally simple because of the current zero which occurs at every half-cycle. It is, generally, at this natural cessation of current flow that interruption is completed in a circuit-breaker, although, as indicated in Chapters X and XI, current may be forced to zero in advance of the natural cycle in certain types of interrupting devices, *e.g.*, fuses and air-blast circuit-breakers.

Expressed very simply, most circuit interrupters consist of current carrying contacts which, under conditions previously determined, separate to isolate the circuit. The majority of circuit-interrupters have two such separate sets of contacts on each pole. Circuit-breakers with four and even six sets have been used with success, while more recently, a single set (known as single break) has been proved equally adequate. This latter development is illustrated in other chapters and is based on the fact that, in a multi-break design, 83 per cent. of the duty is performed on one break. This has been studied in detail by Davies and Flurscheim and reference should be made to the paper by these investigators (see Bibliography).

At the instant of contact separation, an arc is drawn between the electrodes. This arc occurs in a highly ionised gap which is conducting and is maintained by the voltage which now appears across the open electrodes. At the first and succeeding current zeros, further ionisation ceases momentarily and it is during this brief pause that interruption may be achieved if a sufficiently insulating medium can be interposed between the separating contacts. Many factors are involved in this process, known as the de-ionising process, which may take several cycles to achieve. Few circuit-breakers will clear in less than two half-cycles, that is two or more current zeros occur prior to final interruption.

Dielectric strength between the contacts is built up by lengthening and cooling the arc and by the generation of pressure which aids de-ionisation. In the air circuit-breaker lengthening and cooling are the predominant features. In the oil-immersed circuit-breaker the arc is drawn under oil, which is vaporised in the vicinity of the arc in an atmosphere of hydrogen, methane and acetylene. This gas is under pressure, being generated within the confines of a tank, and violent turbulence is caused, which aids the de-ionisation process. In later designs, devices described as arc control pots have been fitted, where the arc is confined to a narrow slot where it

is swept by a jet of oil escaping through exit throats or slots. Here the oil displaces the conducting arc path. In the more modern air-blast circuit-breaker, air at high velocity is directed into or across the arc. Although of weaker dielectric strength than oil, a balance is obtained by the higher velocities possible.

Thus, the general problem of interruption is that of introducing dielectric strength in the arc path at an instant of current zero such that subsequent breakdown of the gap between the separating electrodes will not occur.

Prevention of re-ignition under normal load conditions, or under fault conditions at or near unity power factor is relatively simple. In these cases, the voltage across the contacts builds up along a system frequency sine wave commencing at zero. Interruption occurs at a current zero where the gap is sufficiently long to withstand the growth of this 50 cycle voltage. In the more onerous case, short-circuits must be cleared where the voltage is almost completely out of phase with the current. In this case, the voltage (of the associated phase) is at or near its peak when the current reaches a zero. During the arcing periods, the voltage across the gap is the arc voltage and this is relatively low with heavy current arcs of short length. It is the voltage shown at Ea in Fig. 7-1. At a current zero, the voltage must at

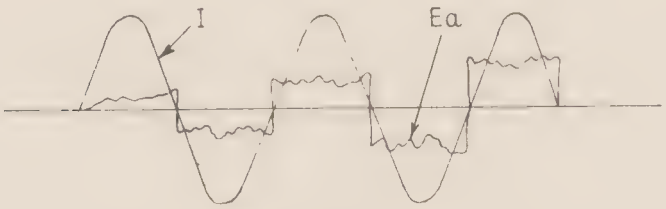


FIG. 7-1.
I = Current.
Ea = Arc Voltage.

once rise to the peak value of the 50 cycle frequency wave. This change not readily observable in ordinary magnetic oscillograms, has been studied by means of cathode-ray oscillograms, and is found to be oscillating about a zero line which is the normal 50 cycle wave of recovery voltage. The frequency of oscillation corresponds to the natural frequency of the system and is determined by the capacitance, inductance and resistance of the system, and its distribution. In a very short space of time (micro-seconds) this oscillating voltage merges by damping into the recovery or normal frequency voltage. Fig. 7-2 illustrates this phenomena. The amplitude of the oscillation is important in circuit interruption. It is determined by the peak value of the 50 cycle voltage at the instant of interruption in each phase. The nature of the fault may also affect the amplitude, *i.e.*, on a three-phase fault in which either the neutral or the fault, or both, are not earthed, the instantaneous voltage across the first phase to clear will be

50 per cent. greater than the line to neutral peak. This is shown in Fig. 7-3 where the blue phase has cleared while the yellow and red phases are still connected via the arcs across the contacts.

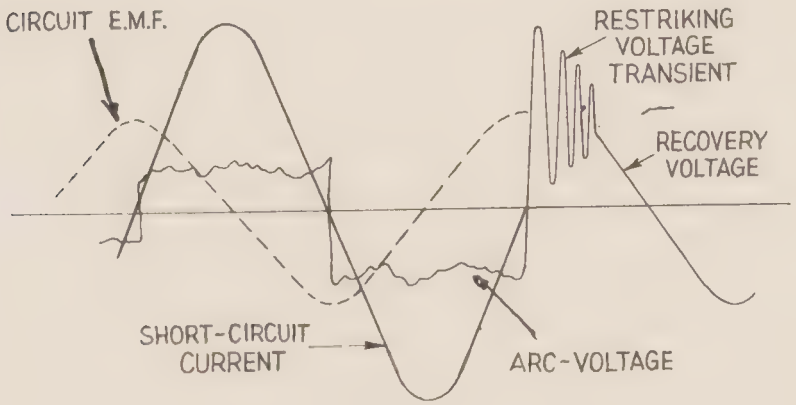


FIG. 7-2.

This condition is catered for in proving tests on circuit-breakers to B.S. 116, etc. From the foregoing, it is seen that the amplitude of this transient voltage oscillation, generally termed the restriking voltage, may be a very high value, the instantaneous peak reaching $2 \times 1{\cdot}5 \times$(phase/neutral peak).

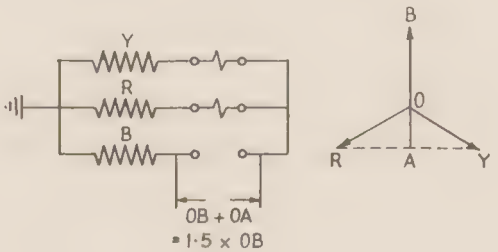


FIG. 7-3.

The oscillating voltage shown in Fig. 7-2 is that of a single frequency transient. In practice, two or more frequencies may be present, depending on the system, resulting in a composite frequency form such as is shown in Fig. 7-4. It is a problem, yet undertermined, how to define the relative severity due to restriking voltage. The method which defines it in terms of "rate of rise" in volts per micro-second is reasonably satisfactory for a single frequency transient. Where more than one frequency is involved,

however, several peaks may occur (as in Fig. 7-4), each having a different " rate of rise." But in this case it may be that the amplitude of the highest " rate of rise " peak is not the most severe. Some other method of defining the restriking voltage is therefore being sought. In all probability, amplitude will be one of the specified factors. " Rate of rise " is expressed by the slope of a straight line drawn through zero and tangential to the front of the curve.

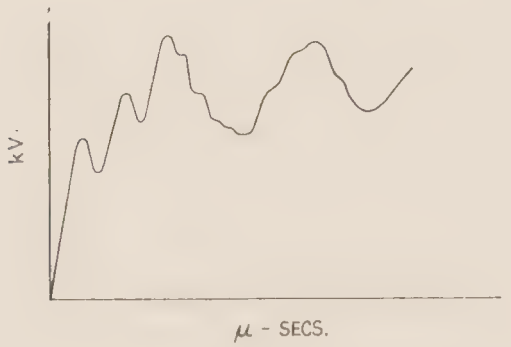


FIG. 7-4.

Since the natural frequency of an oscillatory circuit is

$$Fn = \frac{1}{2\pi\sqrt{LC}}$$

it is clear that Fn will be low for a short-circuit at the receiving end of a feeder as capacitance will be high. At points near the busbars of a power plant and at points close behind transformers and reactors, capacitance will be a minimum and the worst conditions of severity are experienced.

In circuit interruption by air-blast, restriking voltage plays an important part in that the circuit-breaker is sensitive to this transient. For this reason, what is described as resistance switching has been resorted to in axial blast designs. Resistance damps the oscillation and this has been used to advantage by switching-in resistance during the arcing period. In air-blast breakers with cross blast, the problem is solved largely by the resistance of the long arc which is drawn across splitter devices.

With the insertion of resistance, the frequency of oscillation becomes :—

$$Fn = \frac{1}{2\pi}\sqrt{\left[\frac{1}{LC} - \left(\frac{1}{2\ RC}\right)^2\right]}$$

From this it follows that, if the resistance is given a value less than $\frac{1}{2}\sqrt{L/C}$, the oscillatory nature of the transient vanishes and the rate of rise of restriking voltage is kept within the rating of the breaker.

Summing up, it may be stated that the problem of circuit-interruption is one of building up dielectric strength in the arc path at a quicker rate than the stress increase due to restriking voltage. This is the purpose of continued research and has been the driving force in producing the many forms of arc control now used extensively in oil circuit-breakers.

BIBLIOGRAPHY

Switchgear Handbook, Vol. I, W. A. Coates and H. Pearce (Pitman and Sons, Ltd.).

Electric Power System Control, H. P. Young (Chapman and Hall).

Switchgear Practice, A. Arnold (Chapman and Hall).

" The Development of the Single-Break Oil Circuit-Breaker for Metalclad Switchgear," D. R. Davies and C. H. Flurschiem, " Journal I.E.E.," Vol. 79, 1936, p. 129.

" Restriking Voltage and its Import in Circuit-Breaker Operation," H. Trencham and K. J. R. Williamson, " Journal I.E.E.," Vol. 80, 1937, p. 460.

" Restriking Voltage as a factor in the Performance, Rating and Selection of Circuit-Breakers," J. A. Harle and R. W. Wild, " Journal I.E.E.," Vol. 91, Part II, No. 24, December, 1944.

" The Influence of Resistance Switching on the Design of High Voltage Air-Blast Circuit-Breakers," H. E. Cox and T. W. Wilcox, " Journal I. E. E.," Vol. 91, Part II, No. 24, December, 1944.

CHAPTER VIII

OIL-IMMERSED CIRCUIT-BREAKERS

THE art of circuit-breaker design would be a relatively simple matter if the device had no more to do than make and break the normal flow of power in a circuit. As it is, a circuit-breaker must also deal with abnormal conditions which arise when an electrical fault occurs and it is these conditions which make the problem one of difficulty. The nature of these fault conditions is dealt with in other chapters and here it will suffice to say that it is to the end of finding solutions for circuit interruption under fault conditions that the major research of the past 10 or 20 years has been

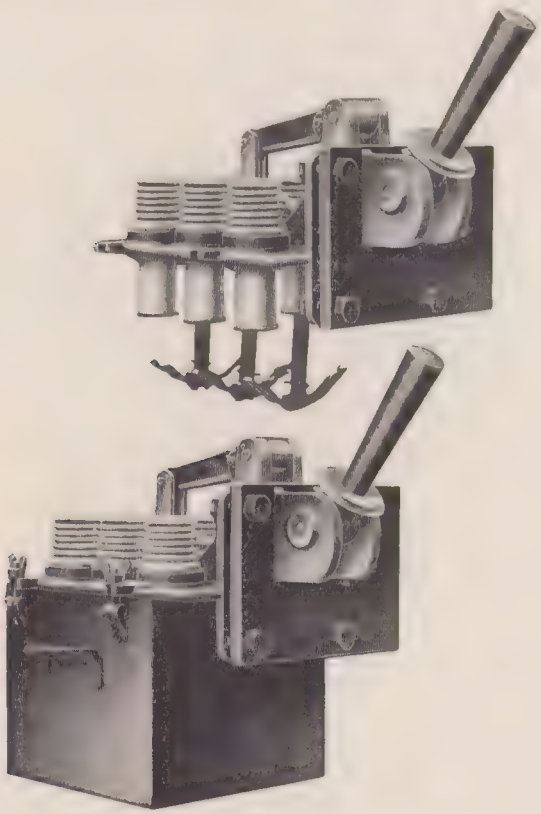


FIG. 8-1—*An early type of circuit-breaker.*

directed. In this country it has been conducted by a number of investigators, notably the B.E.A.I.R.A. (better known as E.R.A.) and many manufacturers, the latter now having the benefit of proving plants at their disposal. Concurrently, research has proceeded at a fast pace both on the Continent and in America, with the result that the amount of knowledge available is very

considerable. The desirable tendency to pool such knowledge is to be commended and to-day a stage has been reached where every confidence can be placed in the modern oil-immersed circuit-breaker, knowing that it will perform consistently and do so under fault conditions at any rate up to, and in most cases exceeding, its rating.

The present-day oil circuit-breaker bears little resemblance to its counterpart of some 20-25 years ago. In Fig. 8-1 is shown an early type of circuit-breaker. The simplicity of the operating handle, and the flimsiness of the contact structure will be at once noted. Compare this with a typical circuit-breaker of the present-day as shown in Figs. 8-2 and 8-3, noting the type of contacts, the fixing of the tank, the mechanism enclosed within the circuit-breaker dome, and other features.

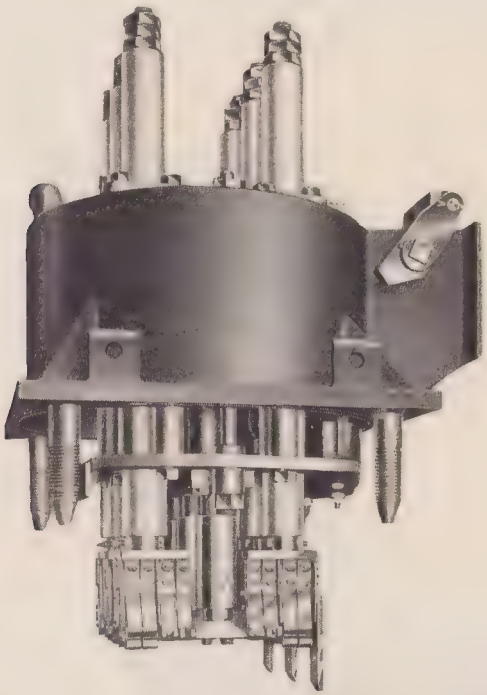


FIG. 8-2.—*Cross-Jet Box Circuit-Breaker, tank removed (J. & P., Ltd.).*

The majority of early circuit-breakers were designed on certain empirical formula, much of which could be called in doubt, and on experience in service. Additionally, a number of factors were regarded by users as having an all important bearing on design and these were compared when a user had to purchase from amongst a welter of offers. These factors were : –

Speed of opening.
Length of break.
Head of oil.
Volume of air cushion above oil.
Strength of tank and top plate.

These do have a bearing but it has been shown that the mere magnitude of any of these factors is no proof of reliability and do not prove a rating. For example, the volume of oil is now a quantity which is reduced to a minimum, and there is more than one design of circuit-breaker of the oil-minimum type where instead of measuring in gallons, this could be done almost in pints. And yet this design has a proved rating equal to that employing many times the quantity of oil. Similarly, speed of break

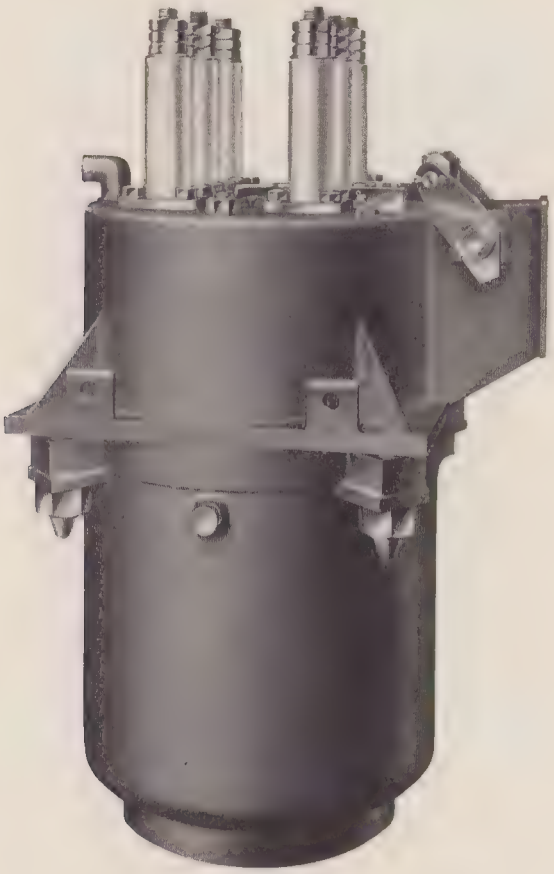


FIG. 8-3.—*Cross-Jet Box Circuit-Breaker.*

is not in itself a sound criterion and in one design, suggestions have been made to deliberately slow up the opening speed. Efforts to increase opening speeds do not necessarily assist in circuit interruption as this tends to increase the length of the arc and thereby its resistance, which means increased energy released in the arc.

The theory of arc interruption has been outlined in Chapter VII. The present chapter will consider the design of circuit-breakers of the oil-immersed type designed to successfully interrupt fault currents.

It will consider both the plain break and arc control types. The former still finds many adherents but the latter is now acknowledged to be a considerable improvement. It is a type used almost entirely at the higher powers, and completely at the higher voltages.

The features of design can best be considered under headings as follows.

FIG. 8-4.—*Close up of dashpot to buffer the moving contact system at the end of the stroke. Piston is just entering the cylinder.*

SPEED OF OPENING.

This has already been commented on. It is a feature which is obtained by the suitable choice of accelerating springs designed to "throw-off" when the retaining catches in the operating mechanism are released. It is assisted under fault conditions by the electromagnetic forces which tend to repel the moving contacts. As this additional effect is dependent on the value of current, the only constant reference speed of opening is that at no-load.

W. A. Coates shows that an approximation of the throw-off force acting on the moving member is given by the formula,

$$F = 20.6 \times 10^{-8} \times I^2 \left(\log_{10} \frac{2S}{d} \right)$$

where F = Total throw-off force in pounds.
I = Short-circuit current r.m.s. amperes.
S = Distance between stud centres.
d = Diameter of contact studs.

High speed of break means strong accelerating springs. This also means that the closing of the circuit-breaker is made more difficult, involving stronger closing mechanisms, and often leading to difficulties when closing a circuit-breaker on to an existing fault.

High speeds also involve complicated forms of buffering to bring the moving parts to rest at the end of the stroke without undue shock. In the smallest breakers buffering is usually accomplished by simple springs; in larger types a piston entering a cylinder of oil is employed. Fig. 8-4 is an example of the latter used on a medium size of circuit-breaker. In this the cylinder is within the circuit-breaker tank and is filled with oil from the tank. This type has one disadvantage in that when adjusting the contacts with the circuit-breaker tank removed, the dash-pot is empty and other means must be made to buffer the shock of opening temporarily.

The speed of opening can be seriously retarded by the pressure set up inside the oil tank, this pressure acting on the moving crossbar. Cases are on record where reclosure has occurred by this means and this particularly arises where the contact lift rod passes through the top plate to atmosphere, as in Fig. 8-1. This is because there is an unbalancing of pressure as between that on the moving system inside and that outside. Hence the majority of modern oil circuit-breakers have the whole of the operating mechanism, except the final link to the handle gear, within the breaker dome or top plate, thus equalising the pressure on all moving parts. This is the case in the design shown in Figs. 8-2 and 8-3.

Length of Break.

This is a function of voltage. It must be such as to have a considerable margin over the length of arc which can be drawn, particularly in plain break designs. A short length of break in which the arc can be maintained across fully open contacts can only result in destruction of the breaker. In arc controlled types, adequate electrical clearance to non-current carrying parts is essential, but in these types it is not anticipated that an arc will be drawn beyond the confines of the arc control device.

Head of Oil and Air Cushion above Oil Level.

The head of oil above the contacts affects gas bubble formation and has a great influence on circuit-breaker performance. The pressures which can be attained within the breaker enclosure are determined by these features. A small volume of air above oil level means a higher pressure for a given volume of gas. This condition however, results in a desirable reduction of arcing time so that no rule can be laid down by which to determine the correct proportions for a given design. The correct values are determined by test and it is important that, in service, the oil level, and in consequence, the air cushion, be maintained at the specified position. It is interesting to note that in certain proving tests, circuit-breaker per-

formance has been improved by the apparently simple expedient of increasing the head of oil by a fraction of an inch and reducing the air cushion by a similar amount. In general, it is found that the air cushion is between 20 per cent. and 30 per cent. of the total volume of the breaker enclosure.

Strength of Tank and Top Plate.

Both tank and top plate must be capable of withstanding the internal gas pressures. The general tendency, particularly in plain break circuit-breakers, is for the oil to be thrown, en masse, upwards into the air space, violently striking the top plate.

In so doing, there is a danger that the top plate may be forced apart from the tank, or at the best, cause an opening between them at the joint through which oil may be forced which, if nothing worse ensues, reduces the oil content to a dangerous point.

At the same time, the pressures act on the tank walls, and it is a feature of design that after fault clearance, there shall be no permanent distortion of the tank. This is usually checked during short-circuit proving tests. As the pressures transmitted to the structure are impulsive, a certain flexibility in the structure is not a disadvantage, providing the undesirable effects stated are not evidenced. It is important to appreciate that in some designs, pressures up to nearly 1,000 lbs. per square inch have been recorded for a very small fraction of a second.

Both rectangular and circular tank constructions are used with equal success. One school favour the circular construction because of its supposed greater strength and the need for a single welded seam only. On the other hand, a rectangular tank can be made equally strong and the school which favours this construction point to the greater volume of oil at or near the two outer phases. In the light of present-day testing, either form can be accepted with confidence.

In circuit-breakers fitted with arc-control pots surrounding the contacts, the internal pressures acting on the main structure are greatly reduced but the pots themselves must be capable of withstanding very high pressures.

The general nature of the internal pressures set up can be judged by the trace marked " fluid pressure " in Fig. 12-12.

Each circuit-breaker enclosure must be vented to prevent a build-up of pressure in successive operations. This vent is located in the expansion chamber above oil level. It must be so designed as to prevent oil throwing and yet allow free passage for gas. This is usually accomplished by an arrangement of baffle plates, pebbles or steel marbles.

The vent must be connected to a vent pipe discharging clear of live parts, preferably outside the switch cubicle or housing, and at a point clear of an operator who might be at or near a switch unit at the moment of discharge. In medium size switchhouses (say up to 250 MVA) it is usual practice to allow venting into the switch room. For higher powers, the vents are taken out through the walls of the room, either separately or via a common header pipe. In the latter case, a non-return valve must be fitted at each junction of vent pipe and header to prevent the discharge from one breaker passing into another.

There are several constructional features in the design of tank and top plate structures which are important. Among these are phase barriers, tank linings, avoidance of obstructions within the top plate, magnetic break-up of top plate for the heavier currents, tank to top plate joint, and the provision of adequate bolting.

Phase barriers are not always provided, but where they are, they usually consist of steel plate welded to the tank sides and, incidentally, giving strength to the tank. In some designs the barrier is continuous ; in others it is in two parts with a central slot which permits movement of a crossbar placed at the bottom of the moving contact system. In the continuous type, it is essential that the crossbar be at the upper end of the moving system. An example of the discontinuous type is shown in Fig. 8-5.

FIG. 8-5.—*Internal view of round tank for circuit-breaker.*

It is common practice to line the inside of the tank (and where used, the metal phase barriers) with an insulating material, such as " Elephantide," or in the smaller breakers, with plywood. This lining is spaced away from the tank sides to provide a layer of undisturbed oil between the lining and the tank.

The design of the top plate in most modern circuit-breakers is in the form of a box, rectangular or circular to suit the tank design, and built of steel plates welded together. This box formation forms the expansion chamber above oil level and houses the operating link mechanism for connection to the external handle gear. In so far as it is possible, the top plate should have a uniform section avoiding the introduction of pockets or projections which may set up unequal distribution of pressure and tending to restrict the mass return of the oil after its first movement. For current ratings above 600 or 800 amperes, it is necessary to break up the magnetic circuits to prevent local heating. In a limited range of circuit-breakers the complete top plate can be made in non-magnetic iron, but in the case of larger breakers it is usual to weld in non-magnetic inserts between the poles. This demands careful workmanship in order not to introduce weak points in the top plate. The use of non-magnetic inserts has been used in one design to provide the basis of an electromagnetic making-current release (see Chapter XIV).

The greatest importance must be attached to the tank-to-top-plate joint, and to the number and size of bolts securing the joint. Two forms of joint

are evident, one in which there are two machined surfaces butting, the other in which there is a gasket or packed joint. A typical design employing both forms is shown in Fig. 8-6 while the plain packed method is shown in Fig. 8-7 ; whatever the form it must be such as to prevent oil throwing in quantity and prevent the emission of flame. The number and size of the

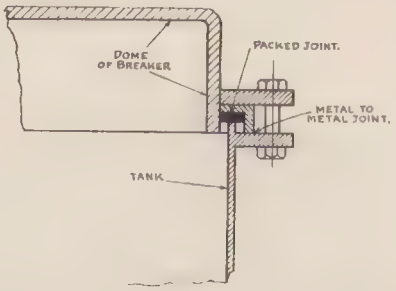


FIG. 8-6.—*Showing the method of making joint between top dome and tank employing both gasket and metal-to-metal. Scale is distorted for clarity.*

fixing bolts must be related to the stresses set up during fault clearance. During this, the tendency is to make the tank and top plate part company but even where this does not occur, elongation of the bolts is a possibility, rendering the joint less efficient and probably useless.

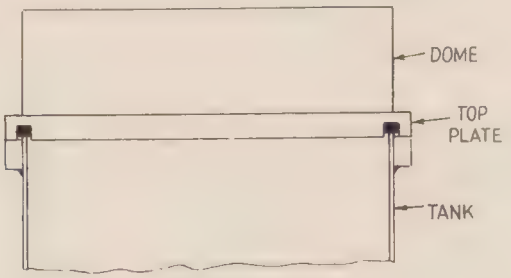


FIG. 8-7.

The elongation may be so slight as to be invisible to ordinary observation so that the initial design is of utmost importance.

CONTACT DESIGN.

Contact design varies very considerably, depending largely on the current to be carried under normal conditions and on whether plain break or arc control is used.

In the latter, the arcing contacts are generally within an arc control pot (an exception is the cross-jet box described later) and it is usually convenient to use a rod as the moving arcing contact, engaging into a socket type of fixed contact. Within reasonable limits this type also forms the main contact as it has ample current carrying capacity up to about 600/800 amps. Beyond this it is usual to fit main contacts outside the arc control device and these would be of the form used in plain break designs.

For plain break circuit-breakers, by far the most popular form is the finger and wedge type shown in Fig. 8-8, which illustrates the circuit-breaker in the open position. This form is easy to assemble and has the advantage

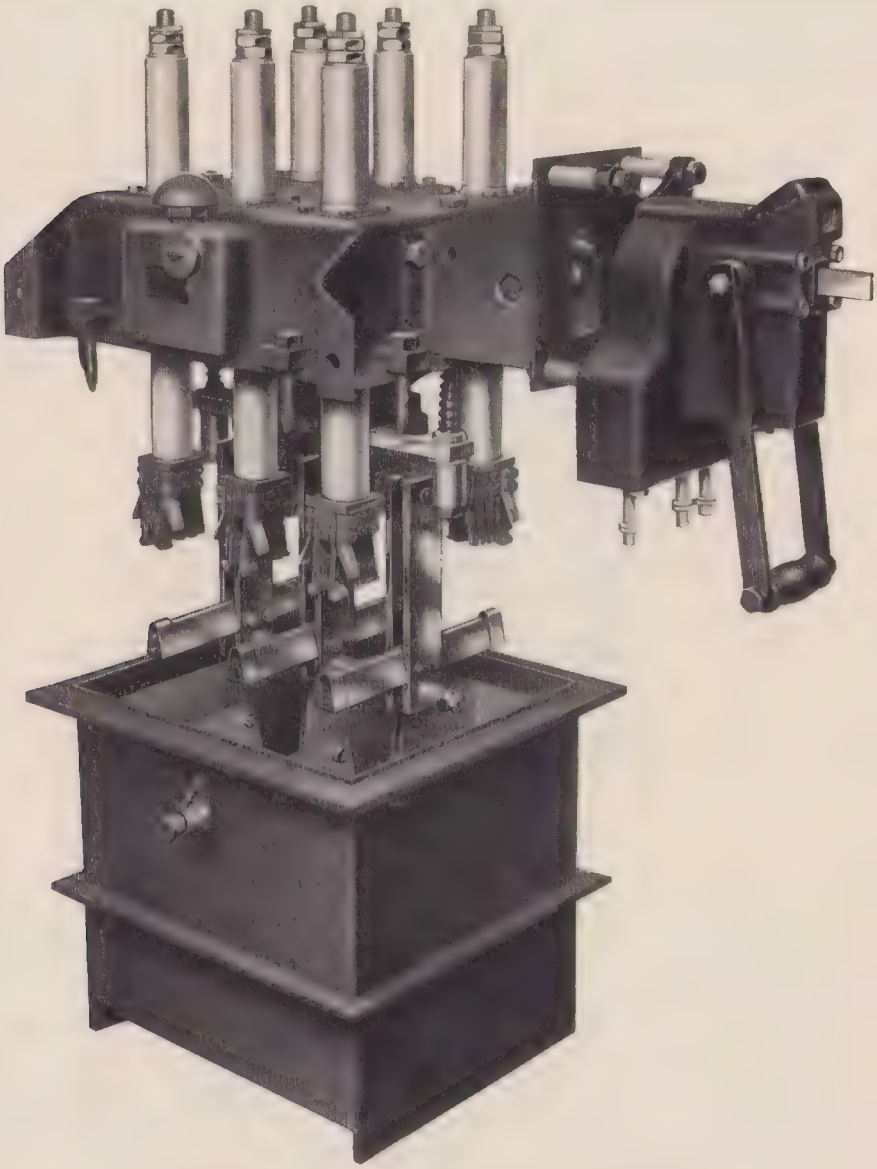


FIG. 8-8.—*Medium current rating circuit-breaker.*

that the fingers of a fixed element can be manufactured in a standard width and the number of fingers varied to suit the normal current to be carried. The type is self-aligning and the vertical position of the wedge shape moving

contact is not particularly important as contact pressure of the fingers is reasonably constant over a range of wedge positions. This pressure is further assisted by mutual attraction of the fingers. The design employs both main and arcing contacts, the latter being disposed as to make first and break last. The moving and fixed arcing contacts must be readily removable for replacement, an essential requirement after a number of fault clearances.

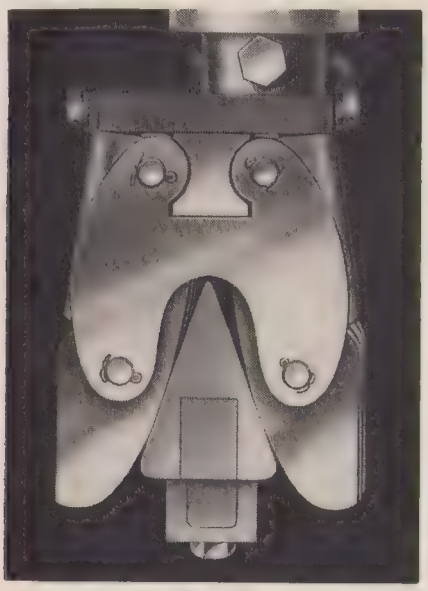


FIG. 8-9.—*Typical Line Pressure Contacts.*

In some designs, more particularly where the fault current to be cleared is over 20,000 amperes, it is the practice to make the arcing contacts of special metal, highly resistant to burning or alternatively to tip the ordinary metals with a thin wafer of arc resisting metal. These special metals are expensive and considerable care is essential in fitting them.

In the finger and wedge contact shown in Fig. 8-8, both fixed and moving elements make contact over plane surfaces. It is recognised that it is not practicable to make two such surfaces touch all over and current is transferred at relatively few points on the surface. Accordingly, later practice has been to employ fingers with curved surfaces and to make contact on a line under high pressure. This is indicated in Fig. 8-9 and tests have proved that given ample pressure, this form is equal to and in many cases better than the plane surface types. It is a form used over many years in contactor design.

Where currents of a few hundred amps. have to be carried, a simple form is the butt contact. This is a form which can be suitably applied in industrial switchgear and Fig. 8-10 illustrates an example. In this, a rolling and wiping action occurs as the contacts make and break and the pressure between them in the closed position is very high.

For very heavy currents, particularly at low-voltage, the brush type of contact is employed. This may take several forms and provides an efficient contact making arrangement, given good workmanship and a high degree of fitting. It can only be used as a main contacting member as it is unsuited to arc breaking and it is usual therefore to associate with the brush a set of butt contacts, spring loaded, which perform the duty of arcing contacts.

A typical circuit-breaker for 3,000 amperes normal rating is shown in Fig. 8-11, a design which has been short-circuit tested up to 30 MVA at 440 volts.

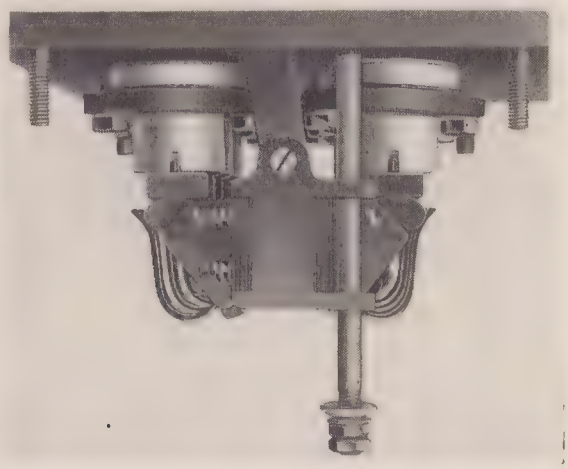


FIG. 8-10.—*Butt Type Contacts under Line Pressure.*

Whatever form of contact is used, it is important to see that low contact resistance is obtained and maintained, bearing in mind that resistance varies inversely as the pressure. Further, it is equally important to remember that when working at reasonably high temperatures, copper oxidises, whether in air or in oil. Copper oxide has a very high resistance and once oxidation has started a vicious circle ensues, as an increase in contact resistance causes further heating, which in turn causes further oxidation, leading to more heat, and so on. In heavy current circuit-breakers these effects are particularly important as they usually operate for long periods in a closed state at temperatures somewhere near the design limit. It emphasises the importance of maintaining contacts in a clean condition, a condition which can be helped by the simple expedient of opening and closing a circuit-breaker a few times at regular intervals. This process is further assisted where line contacts are used as these are self-cleaning in a high degree.

In order to lessen contact resistance silver plating or facing may be resorted to. This is general for the heavier currents but only on the main contacts as silver applied to arcing contacts would be soon destroyed under arcing conditions. Silver so applied not only reduces initial resistance but

also does not increase in resistance at as great a pace as does copper in service.

CIRCUIT-BREAKER BUSHINGS.

For the majority of small circuit-breakers through-bushings of porcelain are entirely satisfactory. Unfortunately, while it is preferred as an insulator, its mechanical strength leaves much to be desired. In compression its characteristics are reasonably good, but when submitted to transverse loads it is extremely poor. The difficulties of firing a porcelain above, say, one inch thickness of wall are well known and this at once introduces a severe limitation on designers. In those circuit-breakers where heavy short-circuit currents have to be dealt with, the porcelain bushing often fails and this has led to the use of a through-bushing of wrapped bakelised paper, wound directly on to the conductor stem.

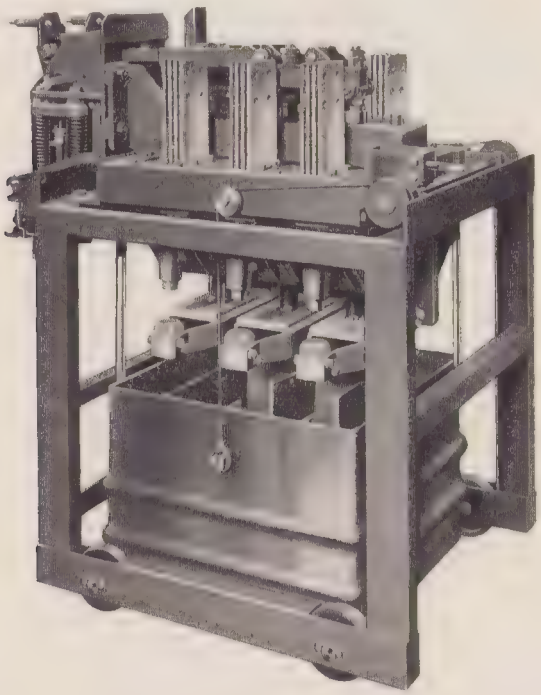


FIG. 8-11.—*L.V. Circuit-Breaker, 3,000 ampere rating. Main moving contact is faced with solid silver (J. & P., Ltd.).*

This form provides considerable mechanical strength and at the same time a degree of resilience. It is entirely suitable for voltages up to and including 11 kV and in certain circumstances, 22 kV. For higher voltages, condenser bushings are used in which layers of metal foil are inserted between turns of the paper at predetermined positions. By correct positioning and length, equal capacitance is obtained between the condensers formed by each foil and intervening paper and the field is thus controlled giving a constant voltage distribution throughout the radial thickness of the

bushing. The building of paper bushings is a specialised art and it is of utmost importance that air should not be trapped between the paper and the mandrel (conductor stem or tube). If air is present at this point, where the electrical stress is greatest, trouble may be expected due to ionisation. It is equally essential that there is close adhesion between the paper and the mandrel so that under the forces applied in closing a circuit-breaker there shall be no movement of the mandrel.

The paper used is varnish treated and is wound on the mandrel under controlled conditions of heat and pressure. In order to ensure good bushings, it is sound practice to check these after manufacture by taking dielectric

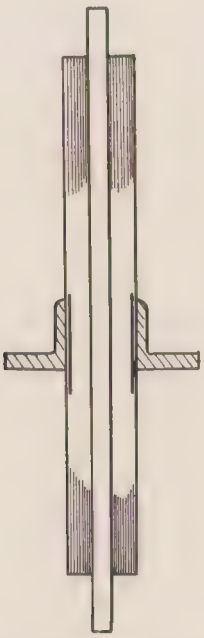


FIG. 8-12.—*Simplified cross section of Bulk (Paper) Bushing.*

tests. These are usually made on a Schering Bridge, taking measurements of the loss angle at various voltages and temperatures. A good bushing will show consistent results up to at least 25 per cent. above normal voltage. A poor bushing will show a pronounced rise often at or just below working voltage. The important point is that there shall be no deterioration in service and in some installations means are provided for regular checks to be made on the condition of each bushing. These results are logged against the values obtained new and each bushing is numbered for this purpose. Detection of deterioration at an early stage may be the means of avoiding a major breakdown later.

Where a bushing is held in a metal flange, as in an oil circuit-breaker, it is usual to embed a metal foil a few layers within the bushing as shown in Fig. 8-12, the foil being connected to the metal flange by a suitable lead. This eliminates the possibility of electrical stress across any air spaces which may be present between the flange and the bushing.

The forces to which bushings can be subject are important. Those due to two conductors carrying current in opposite directions are considered in Chapter XVII. In our case it is the deflection which can occur at the contact blocks at the bottom end of the terminal studs which is important. The magnitude of this can be determined from,

$$D = \frac{14{\cdot}31 \times I^2 \times L^4 \times 10^{-15}}{d^4 \times S}$$

where D = Deflection in inches.
I = r.m.s. value of symmetrical current.
L = inches from point of support on breaker top to face of contact block.
d = diameter of stem in inches.
S = centres of stems in inches.

If *peak* values are to be considered, this expression needs modification as set out in Chapter XVII.

In the case of most through-bushings, the stem is held at its extreme ends while the bushing is rigidly held to the top plate at a point somewhere near the centre of its length. Thus it is the bushing which has to stand the repulsive load and not the stem. Porcelain will only relieve the stems up to its breaking limit.

ARC CONTROL DEVICES.

It has been stated that an oil circuit-breaker has two important functions to perform which are, in some respects, widely separated. The first of these is that of making, breaking and carrying the relatively low value of normal load current for which it is designed, a duty which presents little difficulty. The second is that of making and breaking abnormal currents which arise due to faults on the electrical system and is a duty which is much more onerous than the first. It is towards improvement in this second function that nearly all recent research has been directed in the field of circuit interruption.

The plain break type of circuit-breaker so far described has given excellent service, and continues to do so. Breakers of this type have been proved on modern test plants and, for the lower values of short-circuit rating, will continue to be an economical design.

Nevertheless, successive tests under equal conditions have indicated that complete inconsistency of performance can occur, *e.g.*, there would be a short arcing time on one test and a long one on the next. It is obviously desirable that on the occurrence of a fault, it should be cleared as rapidly as possible, thus causing as little disturbance to the stability of the system as possible ; and to have first a long clearance time and then a short one, is not the ideal.

That the plain break circuit-breaker should be inconsistent can be understood when it is noted that its action is almost entirely fortuitous and unpredictable. For example, except for the confines of the oil tank, there is nothing to control the oil, which may be blown away from the arc by the gas pressure instead of into it where it is wanted. Moreover, the oil is free to be blown in any direction. Thus the primary object of destroying the arc space at the time of an early current zero after the incidence of a fault may only be achieved after seven, eight or more cycles of arcing, this prolonged period adding to the work imposed on the circuit-breaker structure. The problem is then, to provide means whereby aid is given towards the destruction of the conductivity of the arc space and while the

plain break design provides for this in the simplest known form, *i.e.*, by oil blast, it is, as previously stated, fortuitous and therefore some form of control is indicated.

To this end, the past two decades have seen the introduction of a number of forms of arc-control device, the majority of which fall into a category which may be termed self-generating, and one type where magnetic means are employed to position and move the arc into the oil.

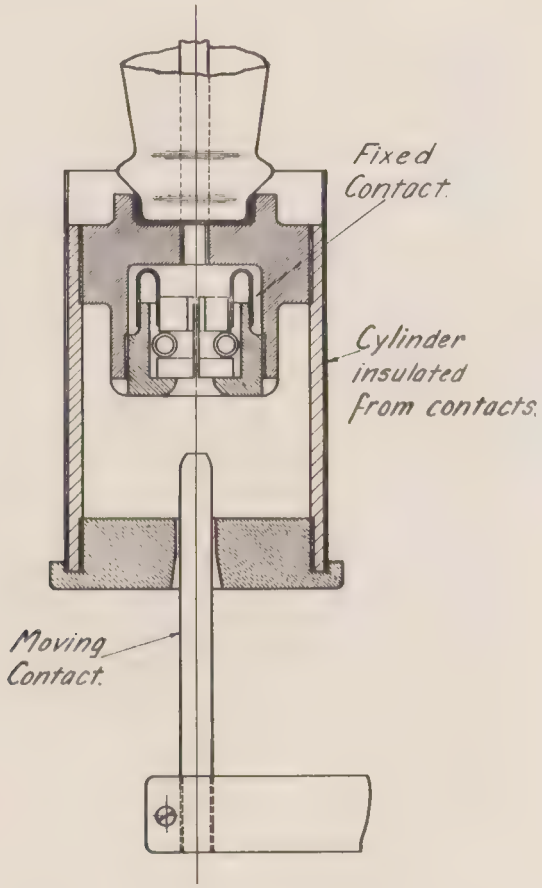


FIG. 8-13.—*Typical early Explosion Pot.*

In its earliest form, the explosion pot was really an arc-control device, although it had none of the elaborations of the more modern device. Fig. 8-13 is typical and comprises a strong insulated chamber mounted as a housing for the fixed contacts, with an aperture through which the moving contact passes. This device functions in such a way that the pressures set up are confined within the pot and when the moving contact leaves the aperture, the oil remaining in the vessel is ejected into the arc path, rapidly cooling and extinguishing the arc.

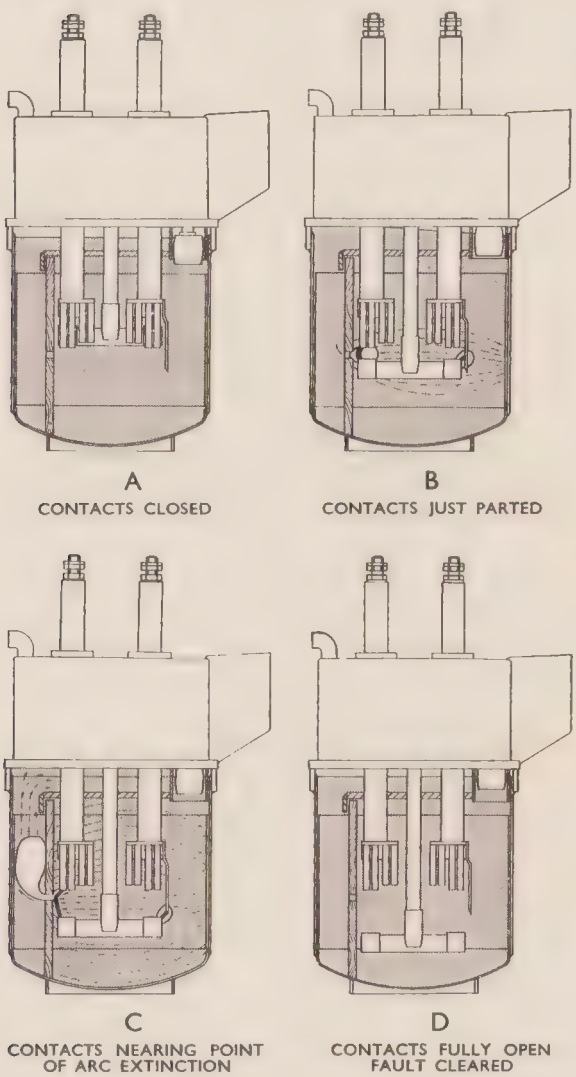


FIG. 8-14.—*Principle of Cross Jet Box Circuit-Breaker.*

Of the more modern forms of arc control device the following will be described as being typical of British practice :—

Cross Jet Box.
Cross Jet Explosion Pot.
Oil Blast Explosion Pot.
De-ion Grid.
Turbulator.

Cross Jet Box.

In this design (used by The British Thomson Houston Co., Ltd., and, under licence, by Johnson and Phillips, Ltd.), the pressure generated by one of the two breaks per phase is utilised to force a blast of oil directly across the arc formed at the other break. The design has the advantage that conventional type wedge and finger contacts are used as in the plain break circuit-breaker with the accompanying ease of replacement and accessibility. The essential difference between this breaker and a plain break design is that the contacts are contained in an enclosure *within* the oil tank. This can be seen in Fig. 8-14, where it is noted that a horizontal

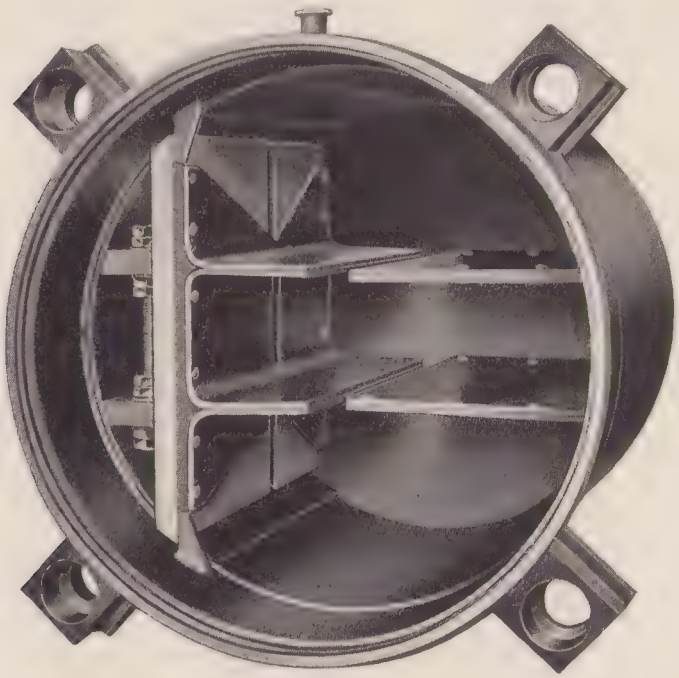


Fig. 8-15.—*Tank for Cross Jet Box Circuit-Breaker.*

steel plate attached to the top plate engages with a vertical plate of insulating material (horn fibre or Permali) fitted inside the oil tank.

These two plates form two sides of a box, with the tank side and bottom completing it. This box within the tank is completely filled with oil. In the vertical plate there are three orifices (seen also in Fig. 8-15), one opposite each pole of the contacts and level with the point of break. The operation of the oil-blast action is illustrated in Fig. 8-14 and briefly is as follows.

When the contacts part, an arc is struck at both sets of contacts, one next to the orifices and one remote. These arcs generate a gas which sets up a pressure within the box, and oil movement results. The box being full of oil, there is no outlet for this movement except through the orifices in the vertical plate. Thus, oil is impelled across the arc near the orifices, through them, and then upwards into the expansion and separating chamber

in the breaker dome. This action is maintained until at an early current zero sufficient oil of high dielectric strength has been forced into the arc path to prevent restriking.

At the contacts remote from the orifice board, arc runners are fitted, the purpose of which is to maintain an arc of constant length sufficient to produce only the pressure necessary to give oil blast. This arc is the generating arc.

Without this runner, the continued lengthening of the arc would result in increasing generation of pressure with consequent increased stresses. It has been proved that a constant length of arc provides efficient extinction. Fig. 8-2 shows a typical cross jet box circuit-breaker with tank removed. The arc runners can be recognised adjacent to the right-hand contacts.

It has been claimed that the operation of an arc-control circuit-breaker is much more consistent than the plain-break type. A " scatter diagram " of both types will illustrate this and such diagrams are reproduced in Figs. 8-16 and 8-17. The first of these illustrates arcing times of the two types and examination shows how for plain breaks, these are longest at the low values of short-circuit whereas in the cross jet box there is consistency at all values. The reduction in arc energy is noted from Fig. 8-17 and these can be summarised as follows.

	10% of rating =15 MVA		30% of rating =45 MVA		60% of rating =90 MVA		100% of rating =150 MVA	
	Plain Break	Cross Jet	Plain Break	Cross Jet	Plain Break	Cross Jet	Plain Break	Cross Jet
Range	70/190	6/28	68/220	10/52	164/435	18/80	166/360	24/160
Average	130	17	144	31	300	49	263	92

All values in this table are in kW seconds and it will be noted that in the cross jet box breaker, the arc energy is within the general rule for arc control breakers stated by Wilson, namely, one kW second per MVA, whereas much higher values occur in the plain break design. Both sets of results given in Figs. 8-16 and 8-17 relate to comparable circuit-breakers, *viz.*, 150 MVA at 11 kV.

Cross Jet Explosion Pot.

In this design (due to the Metropolitan Vickers Electrical Co., Ltd.), the movement of the arc and oil are under complete control. The device is shown in Fig. 8-18 which illustrates the four general stages of operation. The gas formed in the early part of the contact movement generates pressure which causes the oil to flow.

This flow can only be in a direction across the path of the arc, which is driven on to insulating barriers acting as arc-splitters. Oil movement is checked by the pressure of the arc itself until a current zero, when the contents of the pot are ejected across the arc path. It is claimed that to be really effective an oil stream must be directed across an arc and not driven along the arc path. In this device this action is shown in Fig. 8-18, noting that the arc is driven on to " cutting " edges.

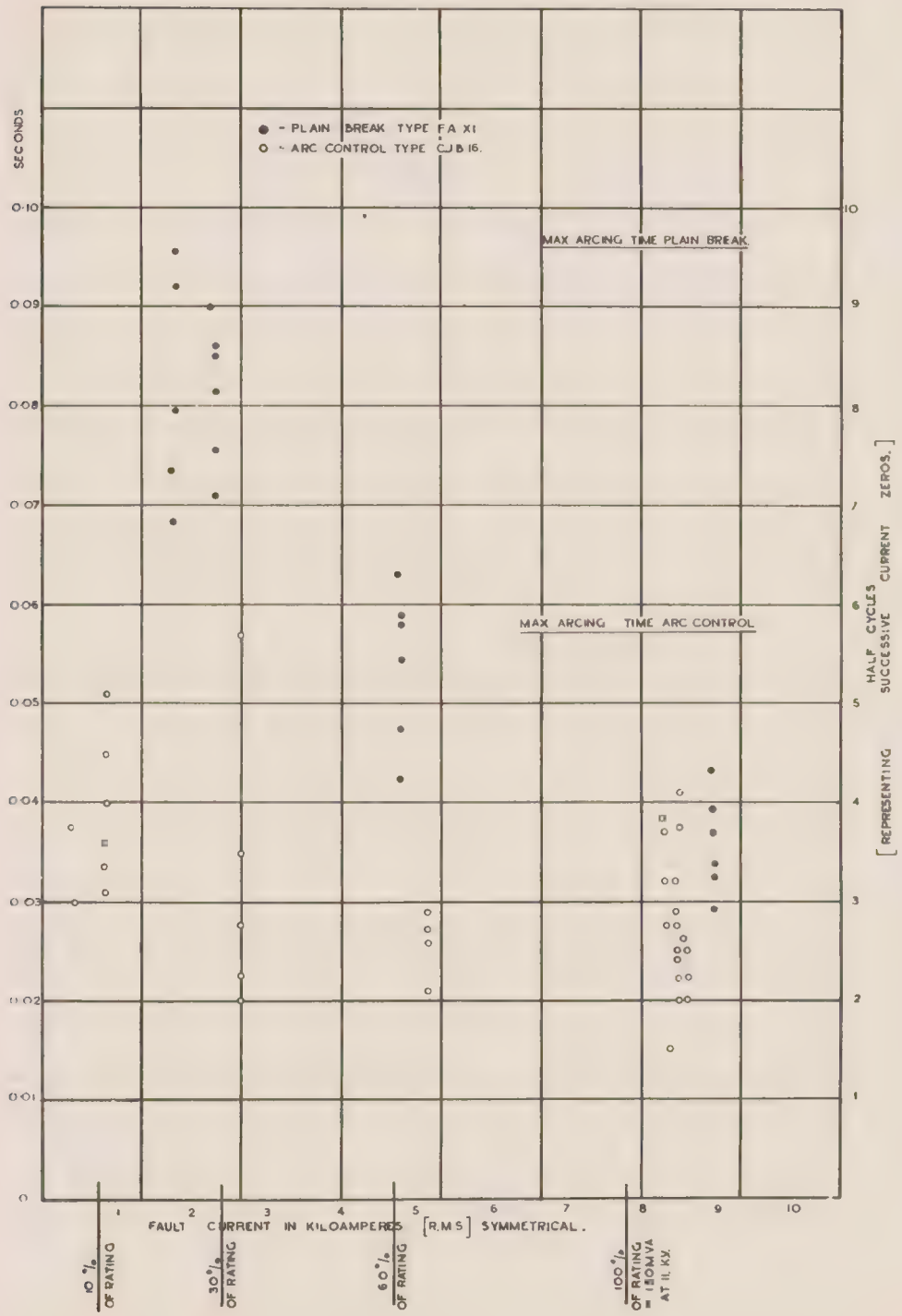


FIG. 8-16.—*Scatter diagram of Arcing Times.*

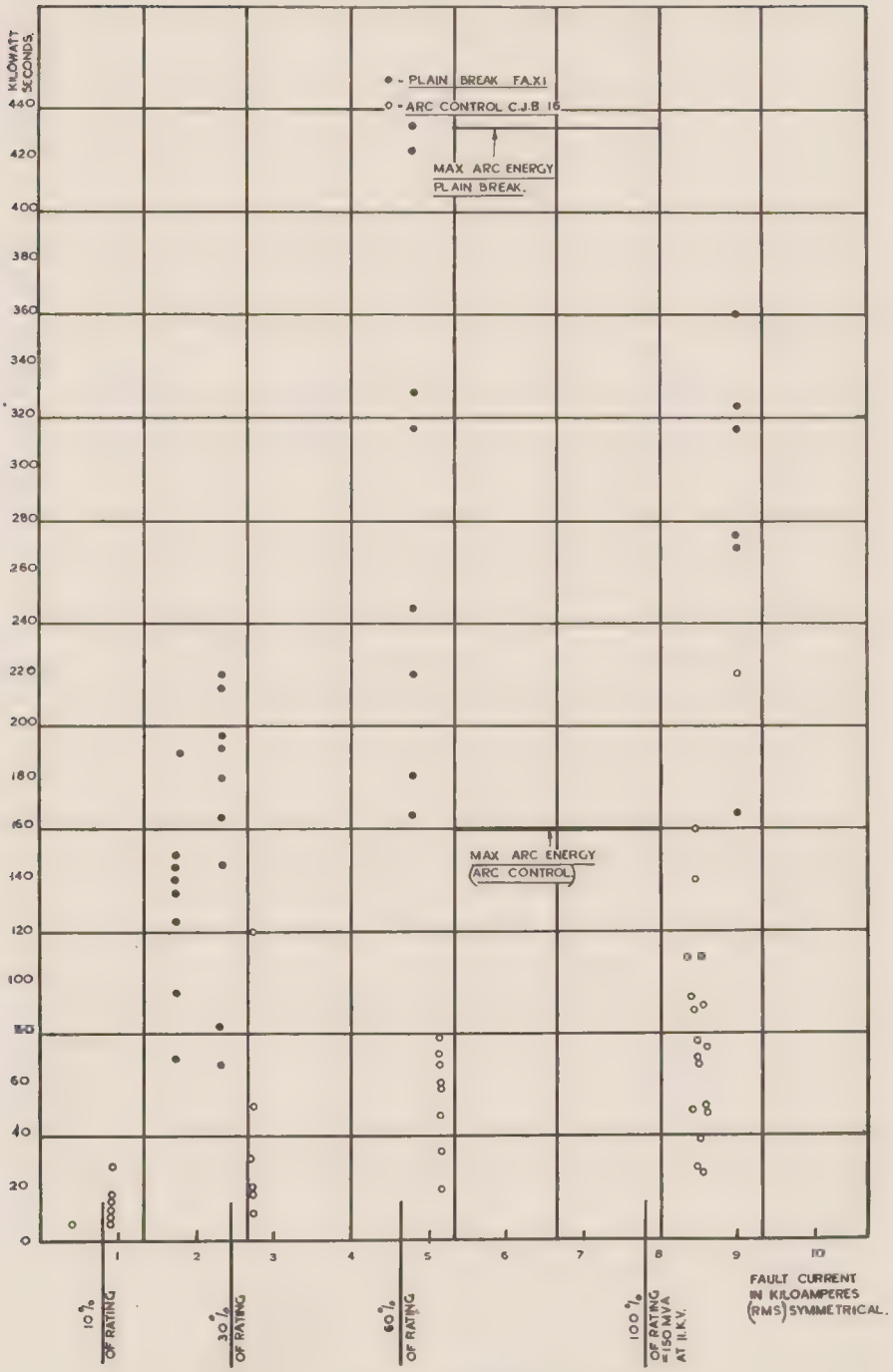


FIG. 8-17.—*Scatter diagram of Arc Energy.*

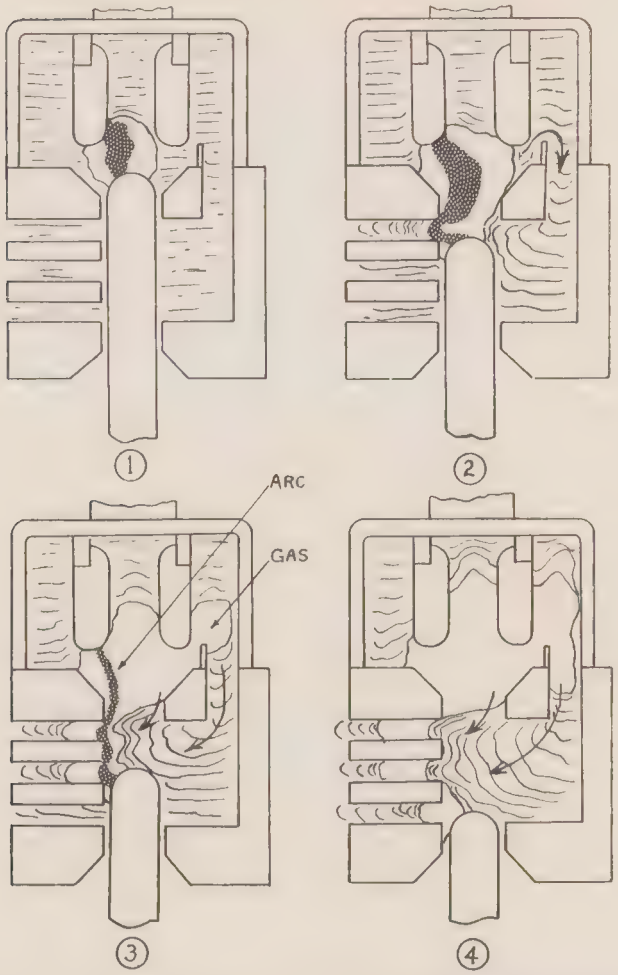


FIG. 8-18.—*Cross Jet Explosion Pot showing four stages of operation (The Metropolitan-Vickers Electrical Co., Ltd.).*

OIL BLAST EXPLOSION POT.

This is an extension of the explosion pot principle and introduces an intermediate contact, thus providing two breaks in series. The first break takes place in the upper chamber, setting up considerable gas pressure therein. When the intermediate contact reaches the limit of its travel, the main moving contact and the intermediate contact separate, and an arc strikes between them. The pressure in the upper chamber forces oil through holes in the plate dividing the two chambers and this oil is forced across the arc and down through the central hole in the moving contact. Thus a quenching effect is produced on the lower arc which is eventually extinguished.

Fig. 8-19 shows a design due to the Metropolitan-Vickers Electrical Co., Ltd.

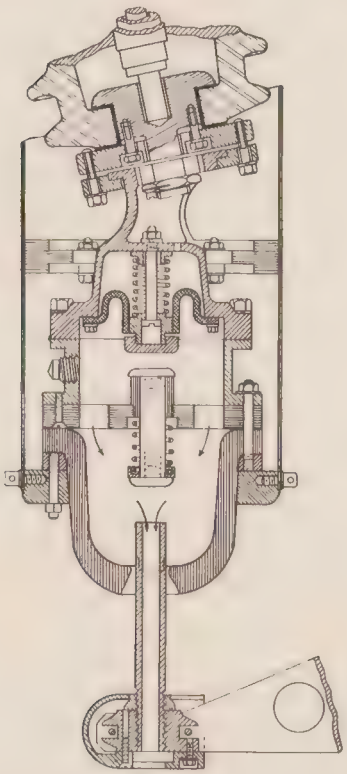


FIG. 8-19.—*Oil Blast Explosion Pot*
(The Metropolitan-Vickers Electrical Co., Ltd.).

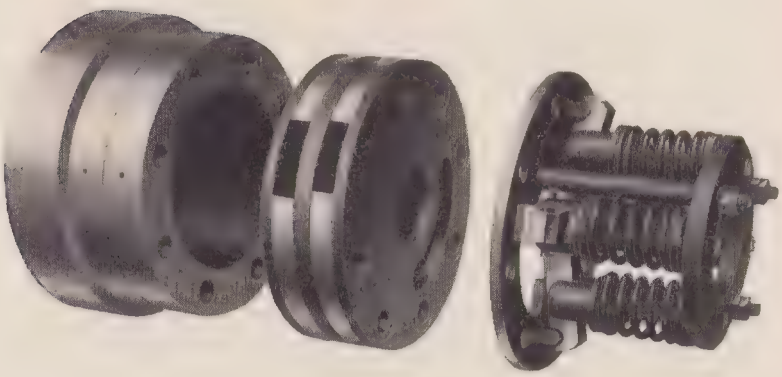
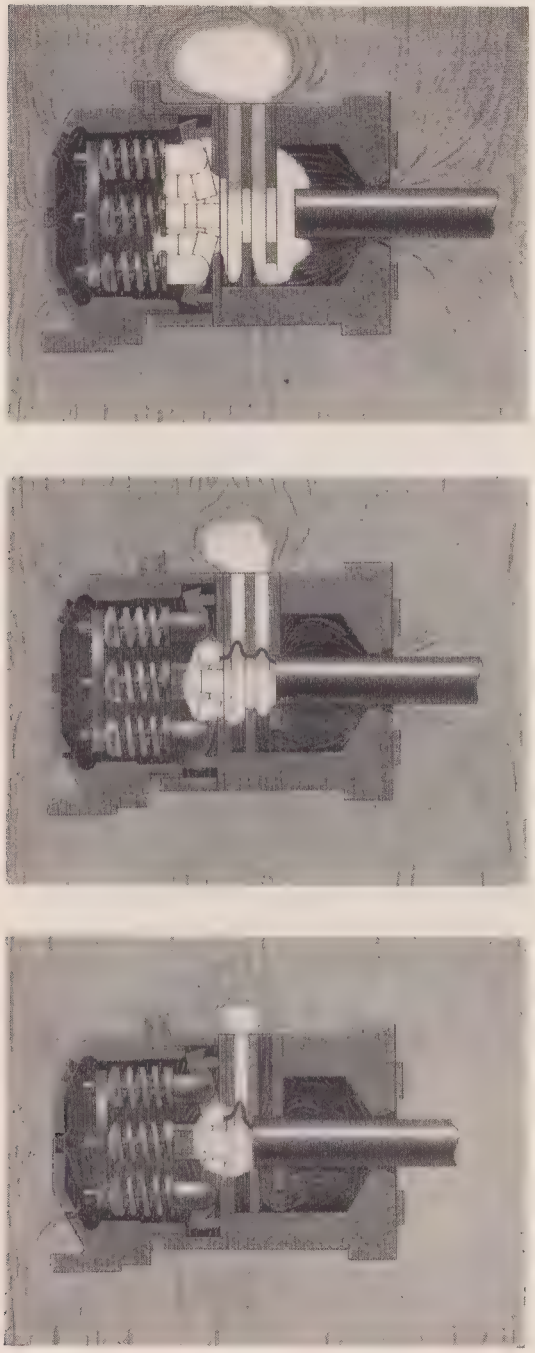


FIG. 8-20.—*Self-Compensated Explosion Pot*
(The British Thomson-Houston Co., Ltd.).



(a) (b) (c)

FIG. 8-21.—*Illustrating the action of the Self-Compensated Explosion Pot (The British Thomson-Houston Co., Ltd.).*

SELF-COMPENSATED EXPLOSION POT.

This form, due to The British Thomson-Houston Co., Ltd., is largely used in single-break circuit-breakers, and combines the features of the plain and cross jet types of explosion pot to secure the advantages of both. The construction is shown in Figs. 8-20 and 8-21 ; the body of insulating material, the baffle or arc splitter plate assembly, also of insulating material, and the contact head. In the example shown butt contacts are used, but segmental contacts are also used in this design.

Fig. 8-21 illustrates the action, from which it is seen that the arc formed immediately after parting of the contacts generates a high pressure gas

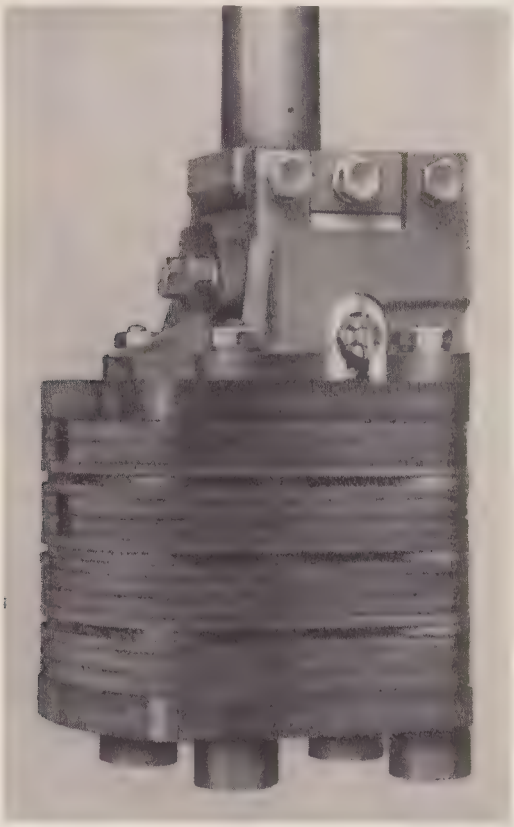


FIG. 8-22.—*Heavy Duty " Deion Grid "*
(The English Electric Co., Ltd.).

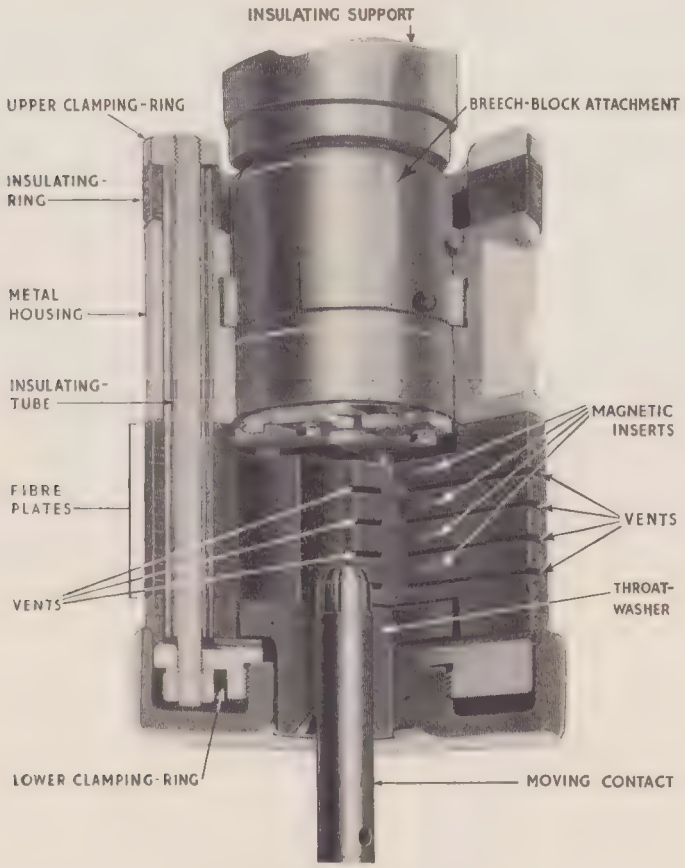
bubble containing oil and oil vapour and forces oil from the upper orifice. The release of gas pressure when this orifice is exposed results in intensive cooling and a sweeping action which forces the arc into the orifice.

At high values of short-circuit current, the gas and pressure formation is so rapid that the arc is deionised and its insulation strength established at the first and second current zero, with only the first orifice exposed. For intermediate values of short-circuit current, the deionising forces are

less and it may be necessary for the moving contact to retract to the position exposing the second orifice. At low values, the sweeping action may last until the tip of the contact rod reaches the throat before the arc path can acquire the necessary insulation strength, so that in this case both side orifices and the throat are utilised. The arc control action is therefore self-compensating over the full range of short-circuit values to be interrupted.

DEION GRID.

This device (used by The English Electric Co., Ltd.) differs in its operation in that the arc is drawn magnetically against the oil as opposed to the oil being drawn across the arc path. Fig. 8-22 shows a typical grid,



The Reyrolle " Turbulator."

FIG. 8-23.—*The sectional illustration above gives an idea of the method of construction adopted in order to provide adequate electrical and mechanical strength, features necessary in order that an arc may be reliably and consistently controlled and extinguished at all loads. The view gives also an idea of the breech-block fitting which enables the device to be easily detached in order to give maintenance to the contacts* (*A. Reyrolle & Co., Ltd.*).

from which it will be noted that it comprises a stack of insulating plates into which iron plates are introduced at intervals. The plates are so shaped as to provide, within the grid, a series of pockets to retain oil in close contact with the arc.

On contact separation the arc is drawn within a narrow groove through which the moving member travels. The presence of iron plates causes the arc to be drawn against the oil while the gas generated can only escape through the arc. As the arc is drawn towards the closed end of the horse-shoe plates the accumulated gases, passing out of the side vents, subject the arc path to a turbulent deionising gas flow.

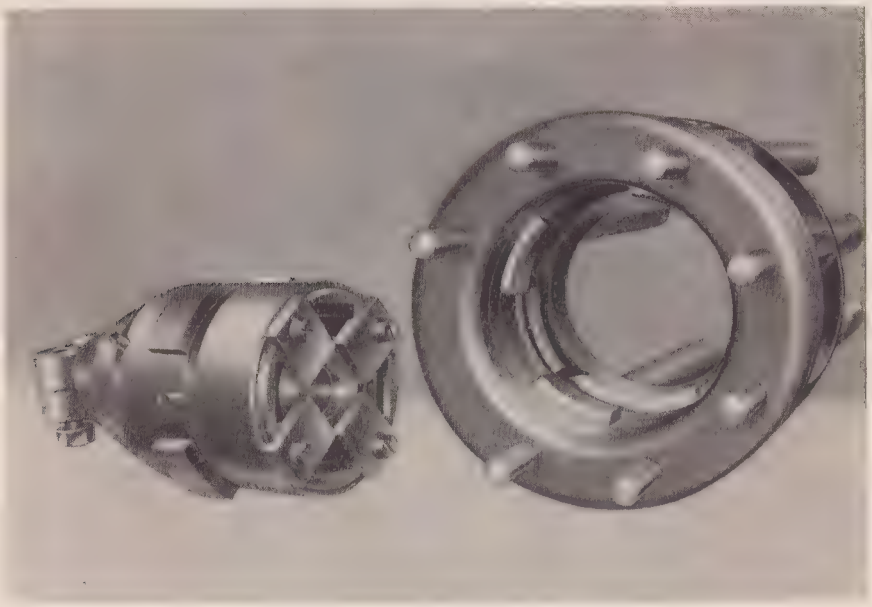


FIG. 8-24.—*" Turbulator " Contact, showing breech block fitting for rapid detachability (A. Reyrolle & Co., Ltd.).*

TURBULATOR.

This design, due to Messrs. A. Reyrolle & Co., Ltd., consists essentially of a device built up of insulating plates, assembled to form an enclosure which is vented by a series of slots or openings. The number of plates used is largely dependent on the service voltage and the number and area of vents is proportioned to the short-circuit current to be controlled. In operation, due to the head of oil in the circuit-breaker tank, the turbulator enclosure is initially full of oil. At the point of contact separation on the opening stroke, the arc is drawn in what is virtually a closed chamber, with the result that part of the oil in the enclosure is vaporised, producing a high pressure. As the moving contact moves further away from the contacts, arcing takes place in front of the vents. By virtue of magnetic inserts, the arc is drawn down the turbulator against the vents, sealing the enclosure during the arcing period. At current zero, the gases generated are first rejected through the arc path at high velocity followed by relatively cooler gas which turbulently cools and deionises the arc path. This action is repeated at each current zero until arc extinction is complete. A typical turbulator is shown in Figs. 8-23 and 8-24.

SIDE BAFFLE.

This device is due to the E.R.A. (Patent No. 366998) and many of the arc-control devices in use to-day are based on this patent. A typical device developed by Messrs. Johnson and Phillips, Ltd., under licence is illustrated in Fig. 8-25. It is generally similar in principle to other devices described, with an enclosure of insulating material (in this case Permali) and with exit vents for the arc products acting across the arc path. The plates which from the stack are shown in Fig. 8-26, these being plates dismantled after

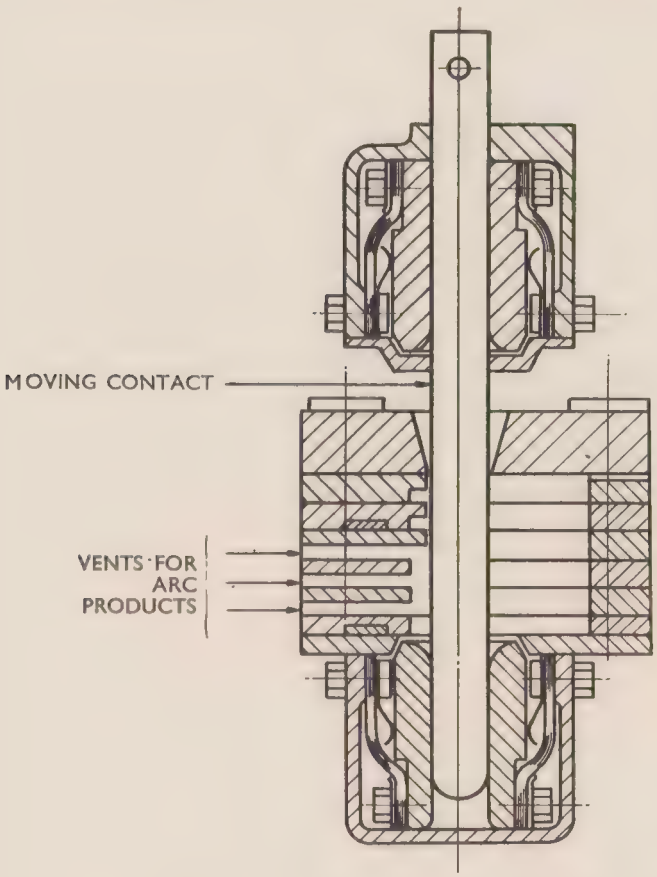


FIG. 8-25.—*Cross-section of Side Baffle Arc-Control Device (J. & P., Ltd.).*

a series of short-circuit tests. In certain plates, slight erosion due to the arc can be noted.

It has been recognised that while at maximum value of short-circuit current the arc-control device is very efficient, at values lower than the maximum, the efficiency may be considerably less. For this reason, among others, the requirements for proving the short-circuit rating of circuit-breakers in this country include tests at 10, 30 and 60 per cent. of rating in

Table I.

Rated Service Voltage 6,600 volts.
Rated Breaking Capacity 6·55 kA at 6·6 kV = 75 MVA. Rated Making Current = 16·7 kA.

Test Duty No.	Test No.	Operating Duty and Time Interval	Breaking Current			Making Current Peak kA	Recovery Voltage between Phases kV	Arc Duration half cycles
			Phase	Symmetrical kA	Asymmetrical kA			
Prospective Current Test	—	—	—	6·60 6·22 6·12	— —	17·7 11·4 14·4	—	—
1 (10%)	1	B	R W B	0·64 0·64 0·63	—	—	6·75	2·6 2·4 1·0
	2	3·5′ B	R W B	0·64 0·64 0·63	—	—	6·82	1·8 2·4 2·0
	3	3·0′ B	R W B	0·637 0·639 0·640	—	—	6·75	1·1 0·7 1·4
2 (30%)	4	B	R W B	2·09 2·03 2·02	—	—	6·62	2·3 2·1 1·8
	5	4·0′ B	R W B	2·12 2·04 1·95	—	—	6·66	1·7 2·4 2·0
	6	3·0′ B	R W B	2·08 2·04 2·03	—	—	6·66	2·5 2·2 0·8
3 (60%)	7	B	R W B	3·84 3·88 3·84	—	—	6·56	2·0 1·6 2·4
	8	3·0′ B	R W B	3·93 3·90 3·90	—	—	6·58	2·0 1·9 1·7
	9	3·5′ B	R W B	3·83 3·86 3·88	—	—	6·60	1·0 2·0 2·0
4 (100%) (Sym.)	10	B	R W B	6·41 6·32 6·04	—	—	6·44	2·3 3·0 2·6
	11	3·5′ MB	R W B	6·76 6·42 6·10	—	16·5 16·0 9·9	6·95	1·6 1·4 2·0
	12	3·0′ MB	R W B	6·56 6·40 5·95	—	10·4 12·0 10·7	6·77	2·5 2·0 2·7
5 (100%) (Asym.)	13	B	R W B	6·86 6·78 6·56	7·62 6·97 6·81	—	6·35	1·8 2·5 2·1
	14	3·5′ B	R W B	6·97 6·82 6·60	8·35 7·00 7·70	—	6·42	2·3 2·0 2·7
	15	3·0′ B	R W B	6·94 6·75 6·53	8·05 7·25 8·01	—	6·34	2·0 1·6 2·3

Test Duty numbers are those in B.S. 116-1937, Part I.

addition to 100 per cent. tests. It has often been found that at some value between 10 and 30 per cent. there is a critical performance. The problem is one of adjustment as while at 100 per cent. there may be ample pressure set up, at 10 per cent. it may be too low. Any modification of the device which increases the pressure at 10 per cent. may result in too high a pressure at 100 per cent.

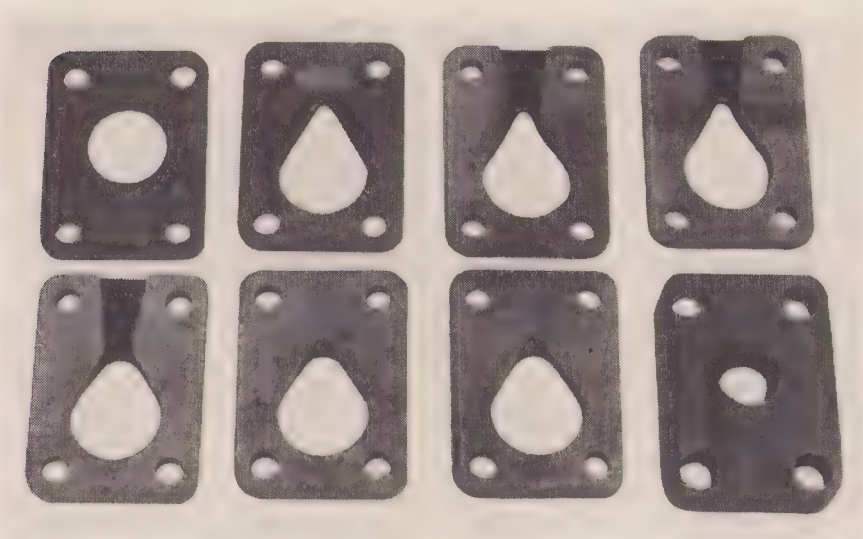


FIG. 8-26.
Component Plates of Side Baffle Arc-Control Devices.

Bearing the foregoing in mind, it is of interest to note the test data for a circuit-breaker fitted with the side-baffle device, this data being given in Table I. From this it will be noted that arc-extinction is equally efficient at 10 per cent. as at 100 per cent. the arcing times showing no sensible differences.

BIBLIOGRAPHY

The Switchgear Handbook, Vols. I and II, W. A. Coates and H. Pearce (Pitman and Sons).

Switchgear Practice, A. Arnold (Chapman and Hall).

Calculation and Design of Electrical Apparatus, W. Wilson (Chapman and Hall).

" B.S.116."

" B.S.936."

" B.S.1086."

" The Development of the Single-Break Oil Circuit-Breaker for Metalclad Switchgear," D. R. Davies and C. H. Flurscheim, " Journal I.E.E.," 1936, Vol. 79.

Electric Power System Control, H. P. Young (Chapman and Hall).

Outdoor High-Voltage Switchgear, R. W. Todd and W. H. Thomson (Pitman and Sons).

" Arc Control Pots," C. J. O. Garrard, " General Electric Co. Journal," No. 10, Page 69.

" Mechanical Integrity in the Design of Electrical Circuit-Breakers," M. C. Hunter, " Journal I.E.E.," 1940, Vol. 87, p. 665.

" Circuit-Controlling Devices," C. W. Marshall, " Journal I.E.E.," Vol. 89, April, 1942.

" Power Factor Tests on Switchgear after Installation," J. R. Mortlock, " B.T.H. Activities," No. 15, p. 71.

" The Mechanism of Alternating-Current Circuit Interruption," H. Trencham and H. Cox, " Engineering," May 28, 1937.

Elements of Switchgear Design, Dr. Ing Fritz Kesselring (Pitman and Sons).

CHAPTER IX

LOW OIL-CONTENT CIRCUIT-BREAKERS

THE oil-break type of circuit-breaker is a well-tried, proved and established piece of apparatus in British designs for use on high-voltage a.c. systems. Nevertheless, it has been argued that if the complete abolition, or at least some reduction in the quantity, of oil can be achieved, progress has been made in that the fire hazard has been also reduced.

On the Continent of Europe, designs of this type, variously described as oil-minimum, oil-less, etc., have been in use for many years, and many descriptions of these have appeared. From these descriptions, it might be assumed that British manufacturers have been slow to appreciate the advantages of oil reduction. That this is not necessarily the case will be shown in the present chapter, but in order to study the problem in proper perspective, it is well, firstly, to review the general position. The demand for oil reduction usually follows an electrical breakdown where ignition of oil from a circuit-breaker tank has added to the effects of the breakdown. In many European countries, such occurrences were, at one time, common, and by force of circumstance manufacturers sought a solution in the oil-minimum or oil-less breaker. On the other hand, a review of electrical troubles in the British Isles would not produce any overwhelming evidence that oil in (circuit-breakers) is a considerable hazard. In this respect, British designers are entitled to take considerable credit for their designs, and users may be praised in the faith they have placed in them without any clamour for radical change.

In considering the oil circuit-breaker let it be agreed that oil, as a quenching and insulating medium, is superior to any other known medium. It is automatic in action and demands no external source of aid, such as compressed air, water, etc. A comment which still holds good was made by Mr. R. W. Gregory in discussing a paper* before the I.E.E. and it may with advantage be repeated here.

> "Oil is not only a good insulator but a superior arc-extinguisher and although it appears logical that reduction in the quantity of oil results in a reduction of fire risk, it does not follow that this is the case.
>
> The oil fire risk is a function of the time and energy required to raise the oil to "flash-point," when a switch is opening on a fault, and to "burning point" when a fault occurs through or in a switch itself.
>
> The more oil there is, the longer it takes for the same fault current to raise it to "burning point" and the more chance there is of the fault being cleared automatically, or discovered and cleared by hand. Cold switch oil is an excellent fire extinguisher, and a large volume of cold oil is, I suggest, much less a fire risk than is a small volume of cold oil. It follows that in oil circuit-breaker design there is logically no need to give special attention

* *See Bibliography (Clothier, Leeson and Leyburn).*

to reducing the amount of oil if this is done purely to minimise fire risk."

This statement may or may not be agreed by different designers or users. It does, nevertheless, express a purely British attitude, and after all, fires in switching stations do not as a rule arise due to circuit-breaker oil unless the breaker fails completely, bursts its tank and spills its contents to feed an incipient fire. As circuit-breaker design has progressed, particularly in the light of present-day knowledge of short-circuit performance, and more particularly as appreciation grows concerning the danger of closing onto faults with inadequate mechanisms, so has the fire danger been reduced. For these reasons, it may be taken that present-day designs will be with us for a long time yet, particularly in the lower voltage and breaking capacity range.

But low oil-content breakers have other features quite apart from any lessening of fire-risk. Chief among these is the important one that reduced oil-content means reduced sizes, and in the higher voltage range, and where short-circuit values are high, this means a very considerable saving in space.

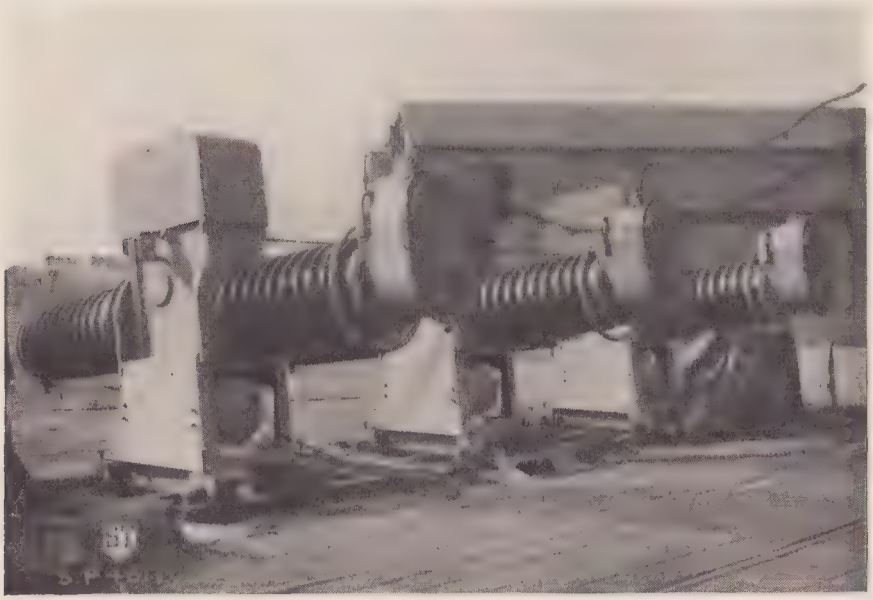


FIG. 9-1.
132 kV Impulse Circuit-Breaker (The Metropolitan-Vickers Electrical Co. Ltd.).

The purpose of the present chapter, therefore, is to describe and illustrate one or two British designs, noting that research still continues and that further developments may be expected.

First of all, it is appropriate to mention a breaker now in use on the 132 kV " Grid " network, a breaker designed by The Metropolitan-Vickers Electrical Co., Ltd., This breaker, comprising three single-phase units, is shown in Fig. 9-1, on the short-circuit test bed. While in this view the

units are floor mounted, in actual practice they are supported on columns at a height appropriate to the voltage and connections of the station. The oil content of a single-phase unit in this design is less than 250 gallons against about 1,000 gallons required for the earlier designs of circuit-breaker for 132 kV.

In addition, it is a design giving extremely fast interruption under fault conditions—a most desirable feature on an interconnected network such as the " Grid," where all steps must be taken to prevent machines falling out of step and causing a widespread shut-down.

Tests on these breakers have shown them to have maximum total-break times of 0.065 seconds.

Fig. 9-2 shows a cross-section of a single-phase unit. It is of the impulse type in which the interruption of the arc is brought about by a jet of oil forced mechanically across the break. The use of a *mechanical* arc-interrupting device ensures equal effects at all values of short-circuit current. In other types, it is known that with the lower values of current there is less pressure developed and therefore longer arcing times.

The breaker consists essentially of a central bushing along the axis of which the moving contact slides. The front end of this bushing is enclosed by a bakelite tube, at the far end of which are the arc splitters and fixed contact. The space between the central bushing and the tube forms the path for the impelled oil, which then returns between the outside of the bakelite tube and the enclosing porcelain rain shield. A stress distributor is fitted at the interrupting end.

Operation of the circuit-breaker is pneumatic from a reservoir, which is charged with compressed air at 150/175 lb. per square inch by a small motor compressor.

In tripping the breaker, air is admitted above the closing piston (4), which then drives the impulse piston (18) to which it is coupled mechanically. For the first half-cycle, the breaker opens extremely quickly; and then, to eliminate any unnecessary drawing out of the arc, the contacts are slowed down again. As this occurs, oil at a pressure of approximately 250 lb. per square inch is forced across the break, thus driving the arc into the splitters and finally extinguishing it. There are actually two breaks, one being opened by the oil pressure against a spring. Opposite each break is an independent set of arc splitters.

After the arc has been interrupted and the oil pressure has returned to normal, this secondary break automatically recloses ; the moving contact is finally retracted to the off position by a spring (16).

This breaker has been designed for breaking capacities up to 2,000 MVA at 132 kV.

Fig. 9-3 shows a design of compound filled metalclad switchgear by The British Thomson-Houston Co. Ltd., suitable for use on systems up to 33 kV and for breaking capacities of 750, 1,000 and 1,500 MVA. The circuit-breaker is of the single-break type, the contact rod moving vertically out of the arc control device. The oil-content is 25 gallons per phase for 750 MVA and 35 gallons per phase for 1,500 MVA. It will be noted that the switchgear is of the isolated phase type, *i.e.*, each phase is contained in a separate metal enclosure, a feature better illustrated in Figs. 9-4 and 9-5.

In this design, not only is the oil-content of the circuit-breaker reduced but there is also a considerable reduction in the compound content. The busbars are of the bulk insulated type, *i.e.*, each busbar consists of a copper

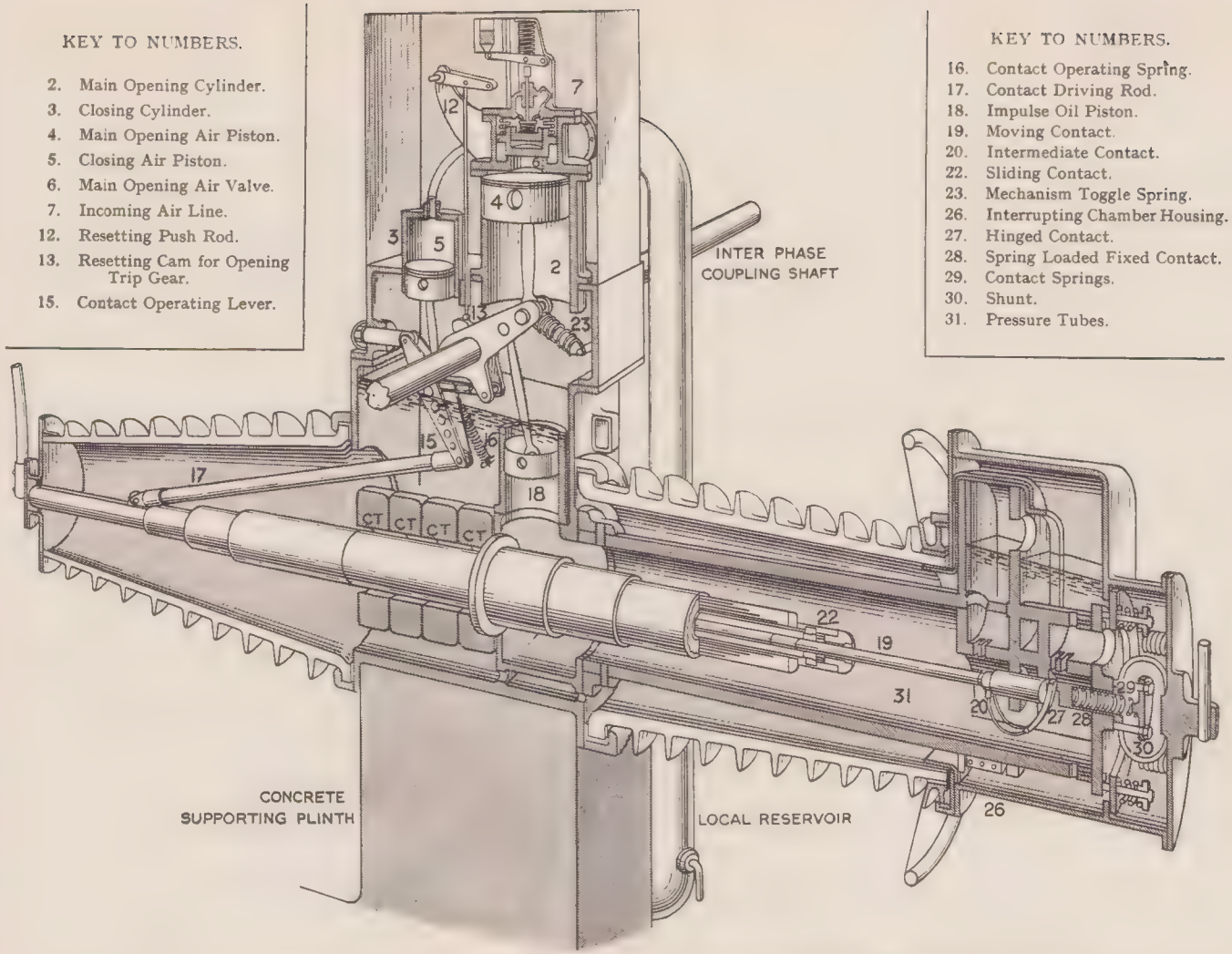


FIG. 9-2.—132 *kV Impulse Circuit-Breaker (The Metropolitan-Vickers Electrical Co. Ltd.).*

conductor wound with synthetic resin bonded paper insulation having condenser layers and protected overall with binding wire.

Messrs. Reyrolle & Co. have introduced a design of metalclad unit in which compressed nitrogen gas is used as an insulating medium in

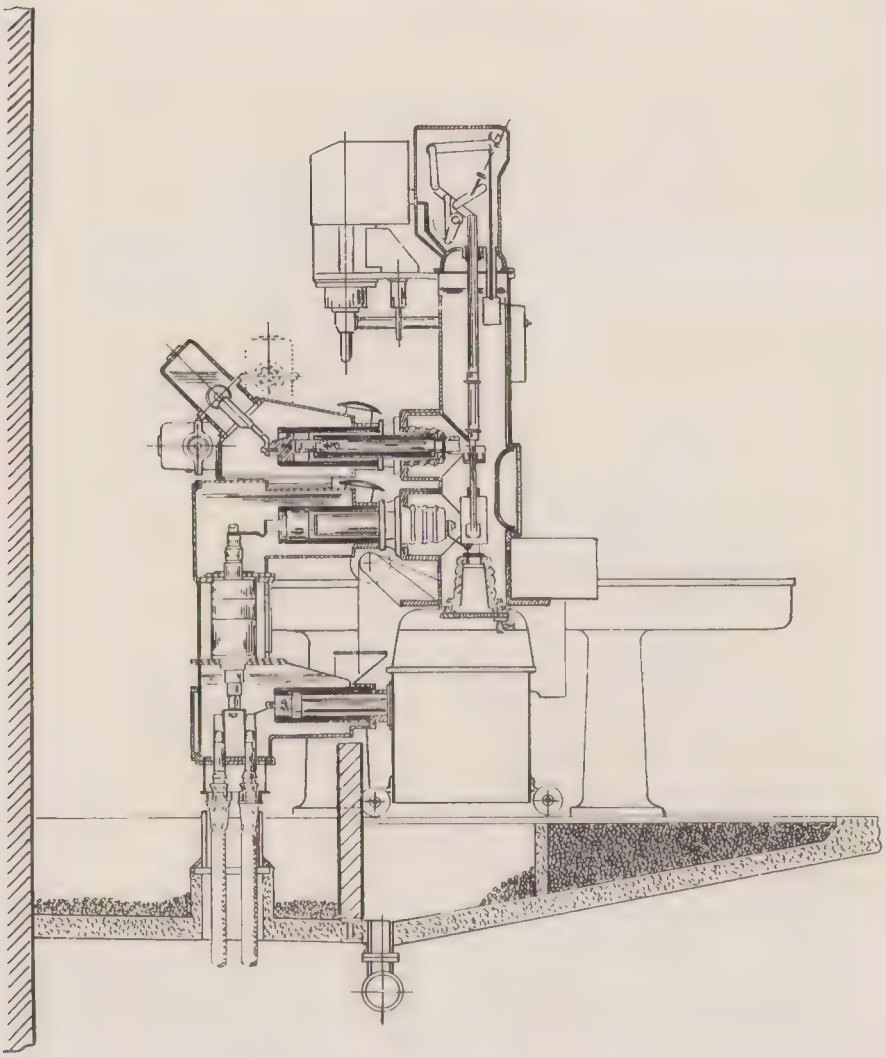


FIG. 9-3.—*Class MF Metalclad Switchgear with low oil-content circuit-breaker (The British Thomson-Houston Co., Ltd.).*

all the chambers enclosing conductors, with the exception of the circuit-breaking chamber. The circuit-breaker itself comprises a minimum oil-content unit enclosed within an outer casing filled with compressed

nitrogen. The oil-content for a 33 kV 1,500 MVA circuit-breaker is only 30 gallons, although approximately another 60 gallons is used for the hydraulic operation of the circuit-breaker and as an insulating medium in the orifice insulators.

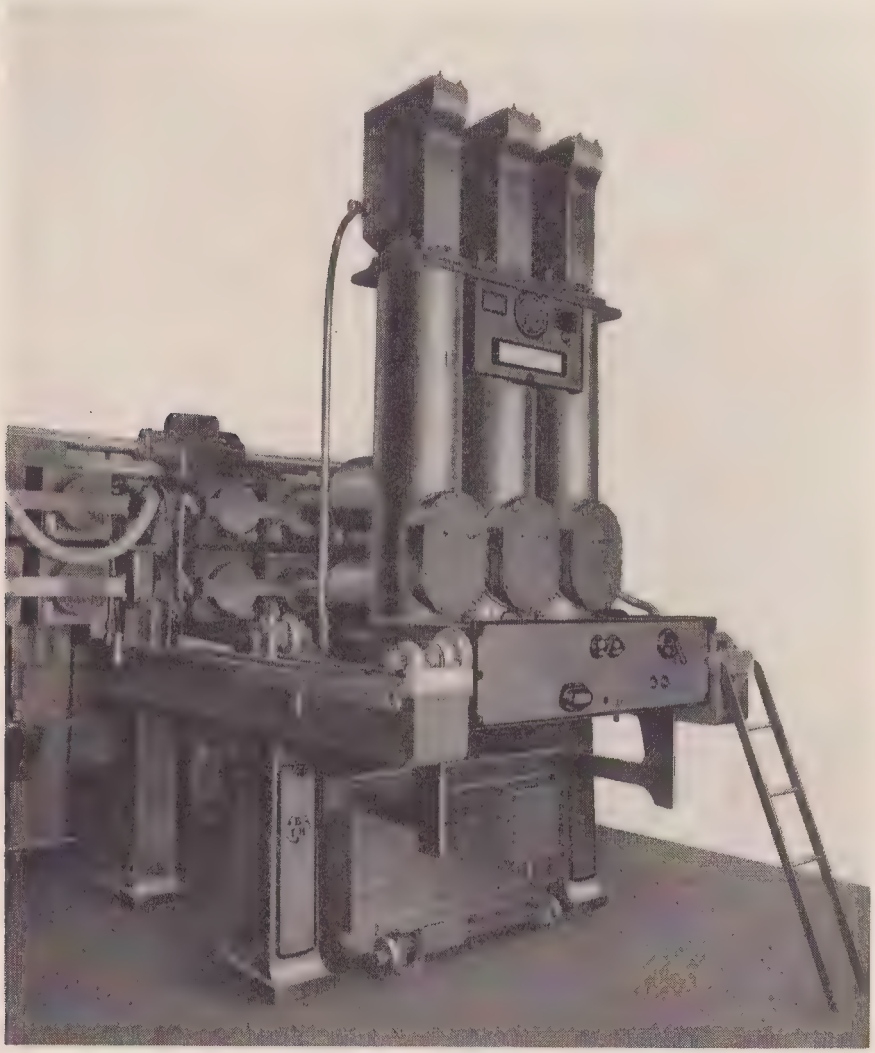


FIG. 9-4.—*Class MF39 Metalclad Switchgear with low oil-content circuit-breaker (The British Thomson-Houston Co. Ltd.).*

Each three-phase breaker comprises three single-break switches with a common top-plate. Arc control devices are fitted (turbulator type). To achieve maximum speed of operation, the inertia of the moving parts has

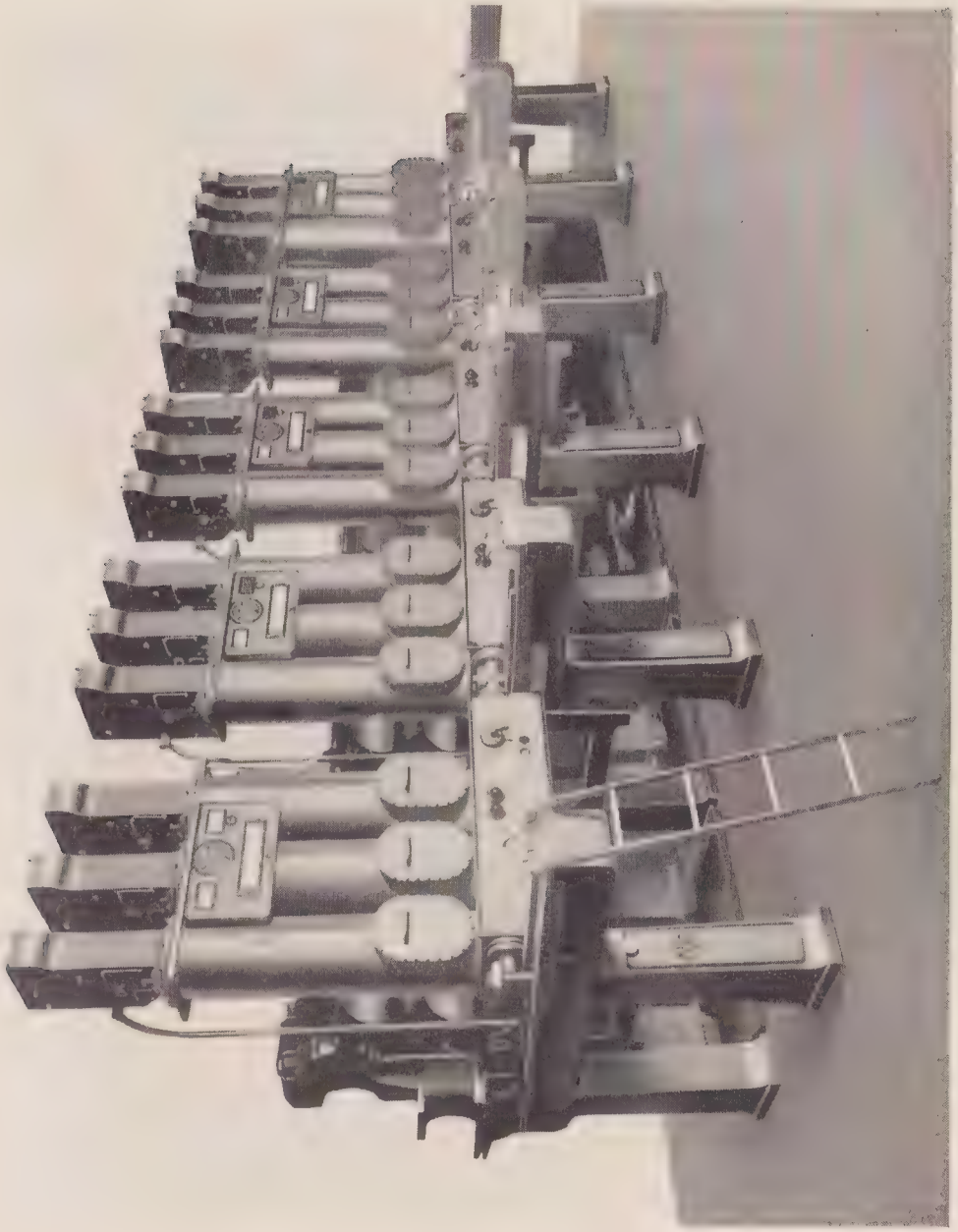


FIG. 9-5.—*Class MF39 Metalclad Switchgear with low oil-content circuit-breaker (The British Thomson-Houston Co. Ltd.).*

been reduced to a minimum by the introduction of a hydraulic transmission system between the operating unit and the circuit-breaker moving contacts. This system consists of a single rod carrying a small piston sliding in a fixed cylinder.

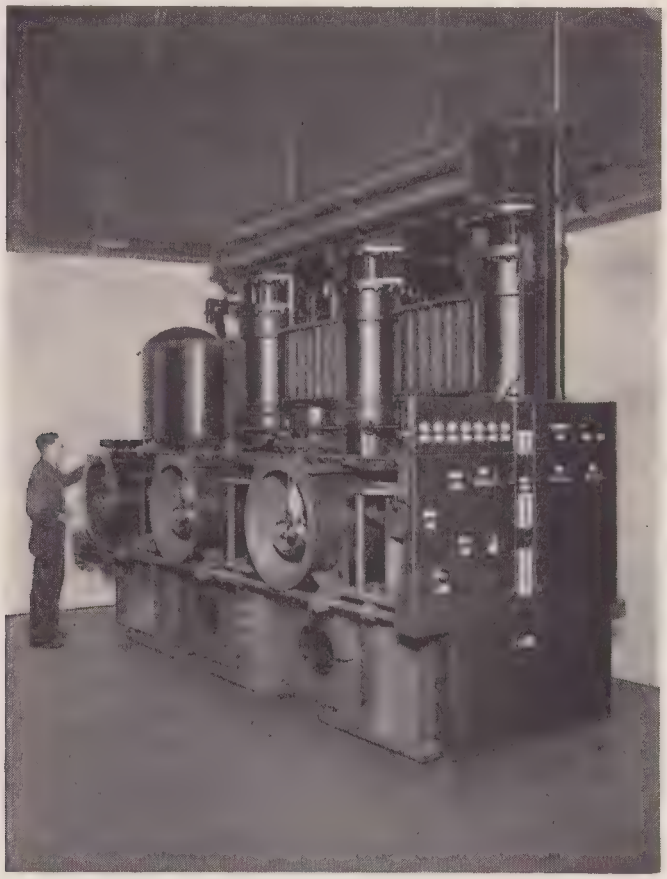


FIG. 9-6.—33 *kV Gas-filled Metalclad Switchgear with oil-minimum circuit-breaker (A. Reyrolle & Co. Ltd.).*

A complete hydraulic cylinder is housed within each of the bushings of the circuit-breaker. A typical unit is illustrated in Fig. 9-6 which shows that the circuit-breaker is supported by a box-type bedplate. A sectional view of this type of gear is shown in Figs. 9-7 and 9-8.

As in other designs, high speed operation is obtained, and in combination with the turbulator arc control device, total break times of 3 cycles (0·06 seconds) or under are obtained. Incidentally, it is interesting to note that the voltage transformers are gas-filled.

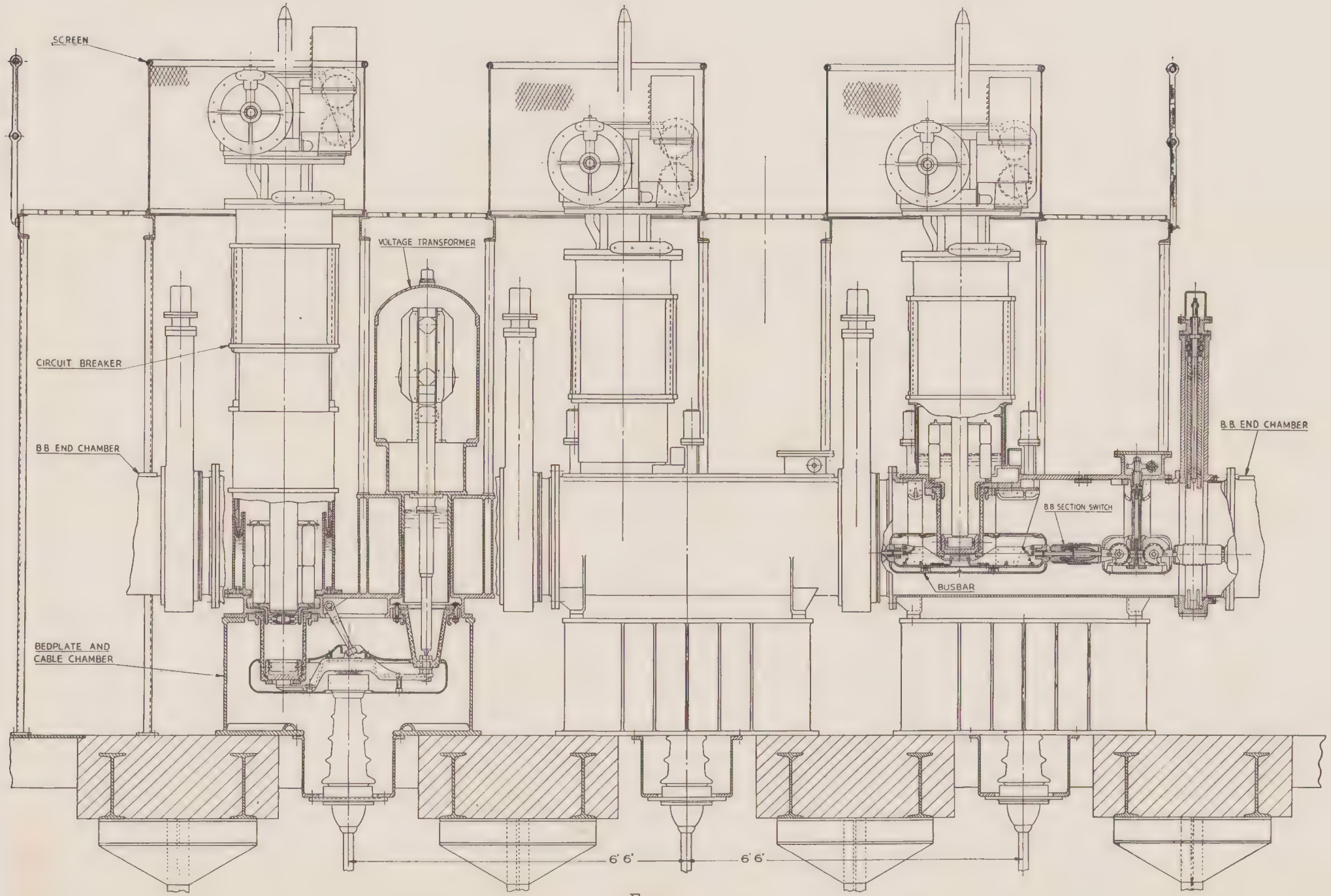


FIG. 9-7.
33 kV Gas-Filled Metalclad Switchgear with oil-minimum circuit-breaker
(A. Reyrolle & Co. Ltd.).

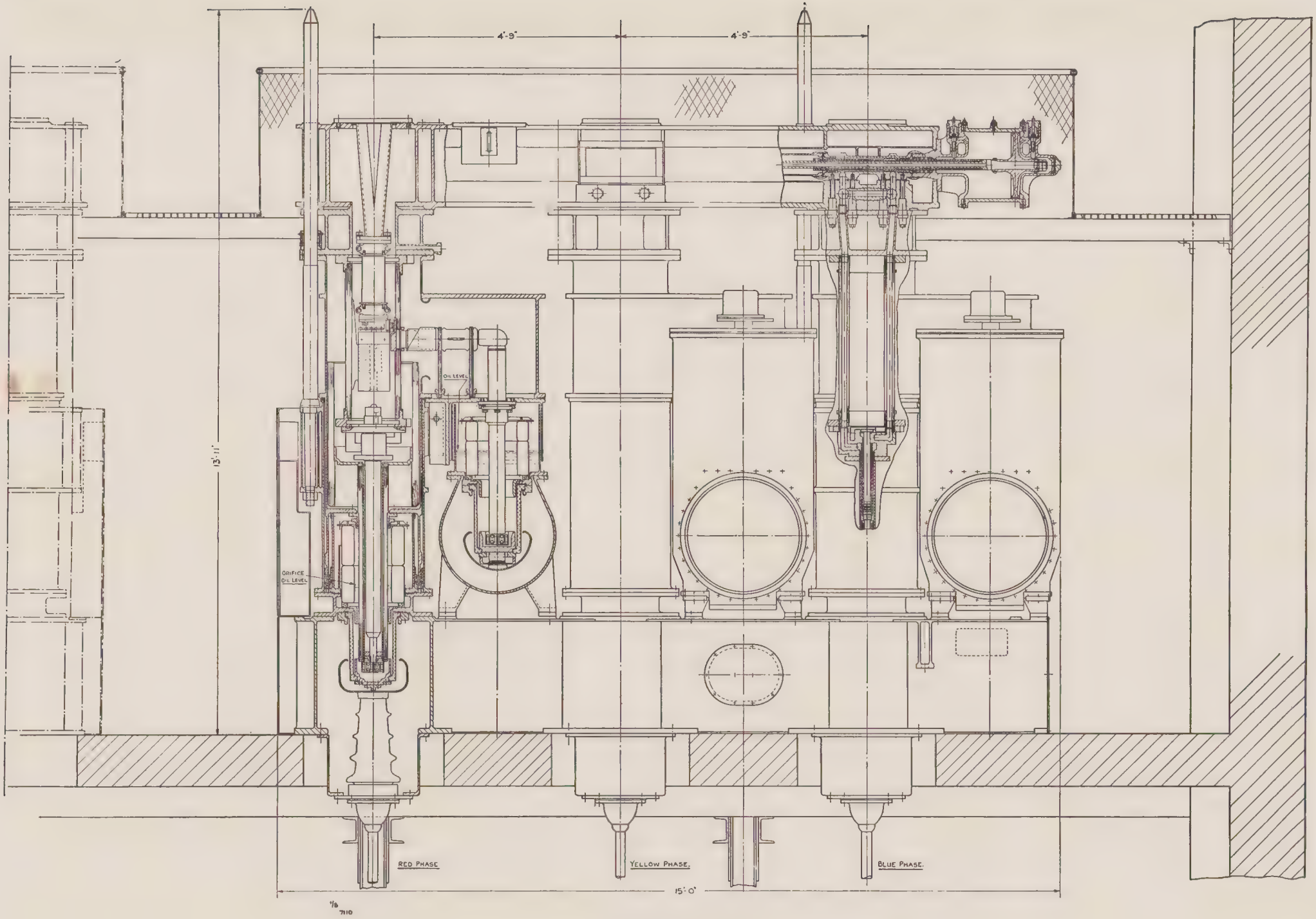


Fig. 9-8.
33 kV Gas-Filled Metalclad Switchgear with oil-minimum circuit-breaker
(A. Reyrolle & Co. Ltd.).

The breakers so far described may be regarded as of recent design, but for many years now, The B.T.H. Co., Ltd., have manufactured a low oil content breaker familiar to electrical engineers the world over, namely the type OH. This design, like all others of any age, has undergone changes in design in line with research into circuit-breaking, so that while retaining the original principles, the modern unit has very much improved performance.

Fig. 9-9 illustrates two sizes of the OH circuit-breaker, and while this is an entirely new illustration, no doubt the general outline will be recognised as one described in switchgear books for many years, often as the "pot" type.

Three sizes are available in this design, namely :

8 INCH OIL VESSEL

Up to and including 1,200 amperes
Up to and including 11 kV
Up to and including 750 MVA

Oil-Content 0·75 gallons per pot or 4·5 gallons per 3-Phase breaker.

10 INCH OIL VESSEL

Ratings from 1,200 to 4,000 amperes
Up to and including 22 kV
Up to and including 1,000 MVA
Oil-Content 1·7 gallons per pot or 10·2 gallons per 3-Phase breaker.

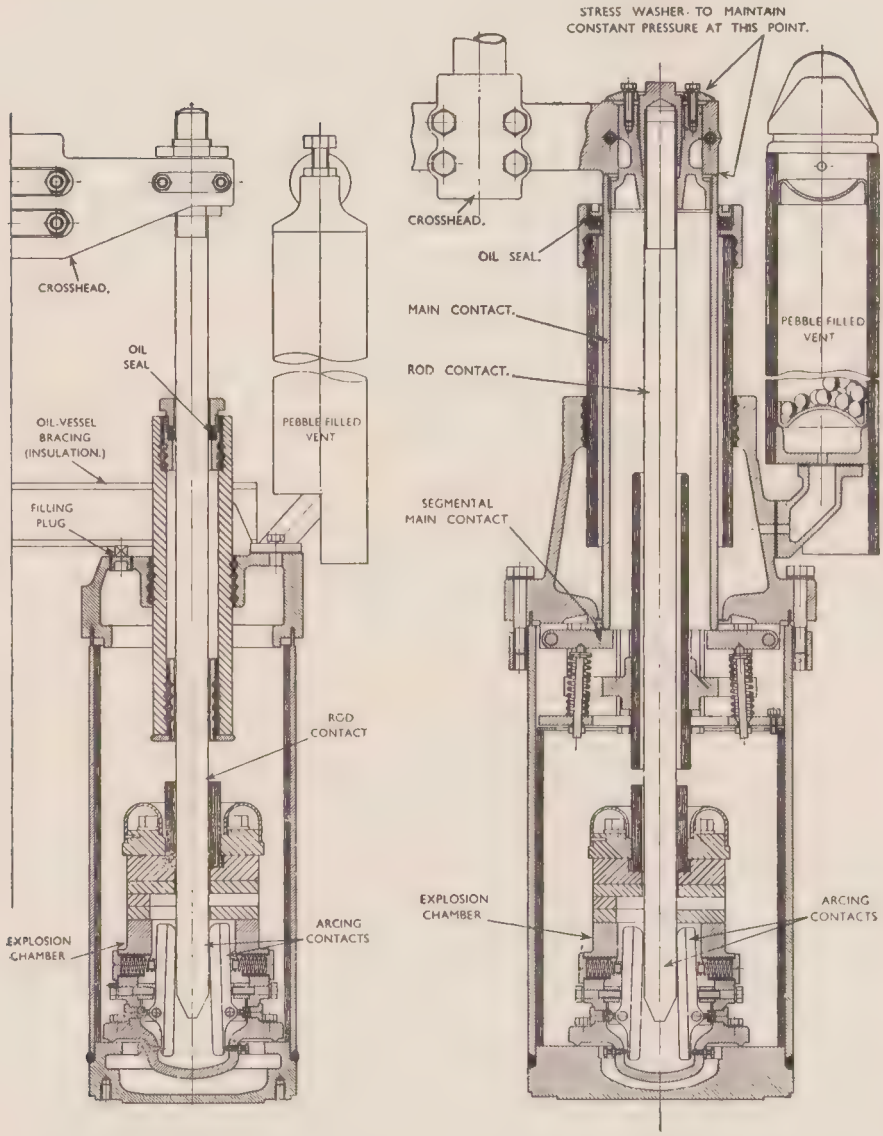
12 INCH OIL VESSEL

Up to and including 1,600 amperes
Up to and including 33 kV
Up to and including 1,500 MVA
Oil-Content 2·5 gallons per pot or 15 gallons per 3-Phase breaker.

The foregoing indicates that the design can rightly be designated "low oil-content."

As the illustrations show, the double-break principle is adopted. In earlier designs, external main contacts were used, but now these are dispensed with. For ratings up to 2,000 amperes, the rod and segmental contacts serve as both main and arcing contacts. This is shown in the left hand picture. For heavier currents, multi-pressure silver line contacts in similar formation are arranged in the head of the oil vessel which engage with a silver plated tubular conductor concentric with the rod (arcing) contact. These form the main contacts and are supplementary to the rod and segmental contacts on which the circuit is made and broken.

In the case of the highest MVA and current ratings, the breakers are fitted with the B.T.H. Company's self-compensated explosion pots with contactor type high pressure pivotted multi-line contacts for 6·6 kV and 11 kV, and butt type contactor contacts for 22 kV and 33 kV. These designs give 5 cycle operation, i.e., the make-break time at full rating does not exceed 0·1 seconds, so that in addition to being of the low oil-content type, they may be classed as of the high speed type.



(*a*) FIG. 9-9. (*b*)

Sectional view of oil-vessel and contacts for Type OH72 oil circuit-breaker, 11,000 volts, 1,200 amperes.

Sectional view of oil-vessel and contacts for Type OH75 oil circuit-breaker, 11,000 volts, 3,000 amperes.

(The British Thomson-Houston Co. Ltd.)

Pneumatic operation is normally recommended, giving closing speeds approximately three times as fast as a solenoid, *e.g.* a 400 ampere breaker has a closing time of approximately 0·35 seconds.

At this point it may be of interest to note that in nearly all designs a single-break (as opposed to the double-break) is employed. This feature contributes in no small degree to oil reduction.

The single-break is the result of research which shows that in a double-break, while current is flowing, the voltage divides equally between the breaks, being controlled by the resistance of the arc path. At current zero, the distribution depends on the relative capacitances to earth and Davies and Flurscheim* have shown that 80-85 per cent of the restriking

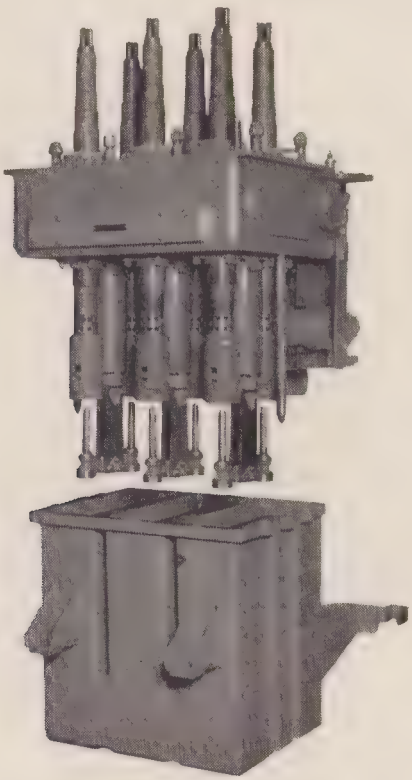


FIG. 9-10.
Low Oil Content Circuit-Breaker (G.E.C.).

voltage appears across one of the two breaks. It follows that the greater part of the duty in maintaining interruption thus falls on one break. The other serves little purpose but draws an arc of equal length, generating an unnecessary volume of gas. This break is the one nearer the earthed fault. Logically, then, new designs have been in the direction of the single break with reduced oil-content.

A low oil content design developed by the General Electric Co., Ltd., has a range of voltages from 6.6 kV to 33 kV and breaking capacities

*See Bibliography.

500 MVA to 1,500 MVA. The circuit-breakers, of the arc control pot type, are of a design which, although retaining the features of simplicity and ease of maintenance which are characteristic of the double break construction, yet have an oil content which is comparable with that used in single break designs. A typical circuit-breaker with tank removed is shown in Fig. 9-10. It is an 11 kV unit, and as is seen, each phase is contained in a separate tank, the three tanks being welded to a common flange for bolting to the top plate. The separate tanks, coupled with the design of the current carrying parts and the arc control pots, allow considerable reductions to be made in size and in consequence, the oil content. The arc control pots are of the side blast type.

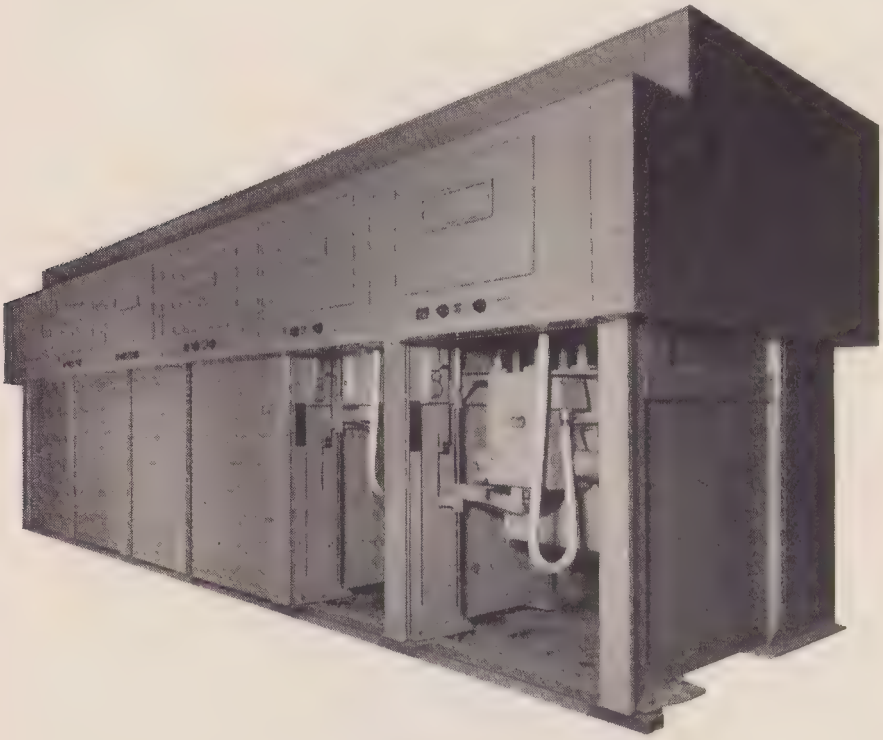


FIG. 9-11.
Metalclad Switchboard with low oil content circuit-breakers (G.E.C.).

In this range of gear, there is complete phase separation, and each unit is enclosed in dust-proof and fire-resisting covers with roller shutter doors, a typical example being shown in Fig. 9-11. Vertical isolation is provided to avoid the use of horizontal spout insulators and this eliminates the possibility of trouble due to tracking following an accumulation of dust and moisture.

A further example of low oil content design, with only a single-break, for voltages 33 to 132 kV is exemplified in the type OS developed by A. Reyrolle & Co., Ltd. This has, as the basis of the arc interrupting chamber, the Reyrolle turbulator arc control device.

A cross section of a single-phase unit of a 33 kV or 66 kV circuit-breaker is shown in Fig. 9-12, the difference for the two voltages lying only in dimensions. It consists essentially of two portions, the lower of which provides insulation from earth and supports the upper, which contains the circuit-breaking chamber. This is a bakelised paper cylinder enclosed in a shedded porcelain. Above it again is a centrifugal separator which allows the gases generated on short-circuit operation to escape without loss of oil. The oil in the circuit-breaking chamber is the arc-quenching medium and requires reconditioning after clearance of short-circuits; the remainder, in the lower portion and in the space between the circuit-breaking chamber and the porcelain in the upper portion is used for insulation only, and is not contaminated. For the 33 kV design the three-phase oil content varies between 30 and 40 gallons depending on breaking capacity, which ranges from 500 to 1,000 MVA.

At 66 kV, 45 to 65 gallons of oil are necessary, again varying with breaking capacity, which at this voltage ranges from 500 to 1,500 MVA.

The turbulator, the general principles of which have been described in Chapter VIII, consists of blocks of insulating material assembled to form an enclosure vented transversely by a series of slots. Magnetic bias is provided to direct the arc towards the vents and thus keep it in the most favourable position for extinction. The moving contact member consists of a metal tube of an outer diameter slightly smaller than the throat of the turbulator. A fixed piston is fitted within the tube, and when the tube moves downwards on breaking circuit the column of oil inside it is forced into the turbulator. This has two purposes: first, pressure balance is ensured, so that the pressure generated inside the turbulator has little effect on the acceleration of the contact and a controlled uniform opening-speed is maintained at all currents; and, secondly, oil passing into the turbulator prevents the formation of a void on the withdrawal of the moving contact.

The breakers are pneumatically operated, an air reservoir being provided on each circuit-breaker framework, with the control mechanism in a separate weatherproof cubicle. This arrangement is shown in Fig. 9-13, where, for the purpose of illustration, the compressor unit is shown within the base of the framework. A 66 kV circuit-breaker is shown in Fig. 9-14.

In the 110 and 132 kV designs, the electrical clearances to earth are such that it is necessary to surround the switchgear by earthed screens. Each single-phase unit has its own compressed air operating mechanism. At 110 kV, the breaking capacity is 1,000 MVA, with an oil content of 66 gallons, while at 132 kV, the breaking capacity is 1,500 MVA and the oil content is 78 gallons. In both cases the oil content is for the three phases.

A design having a *reduced* oil content, although not of the true low oil content type, has been developed by Crompton Parkinson, Ltd., A typical cross-section is shown in Fig. 9-15.

This circuit-breaker is of the single-break type operating horizontally. The basis of the design is the E.R.A. side baffle device (see also Chapter VIII) modified to a patented arrangement to provide a compensating device which ensures that correct pressure is generated for arc extinction, even under conditions of very small highly inductive loads, and to provide relief of pressure when dealing with maximum ratings which are in excess of requirements in extinguishing the arc and which might even cause damage to the chamber. Fig. 9-16 gives more detail of this arc-extinguishing device, from which it is seen that the back plate, which also carries the fixed contact

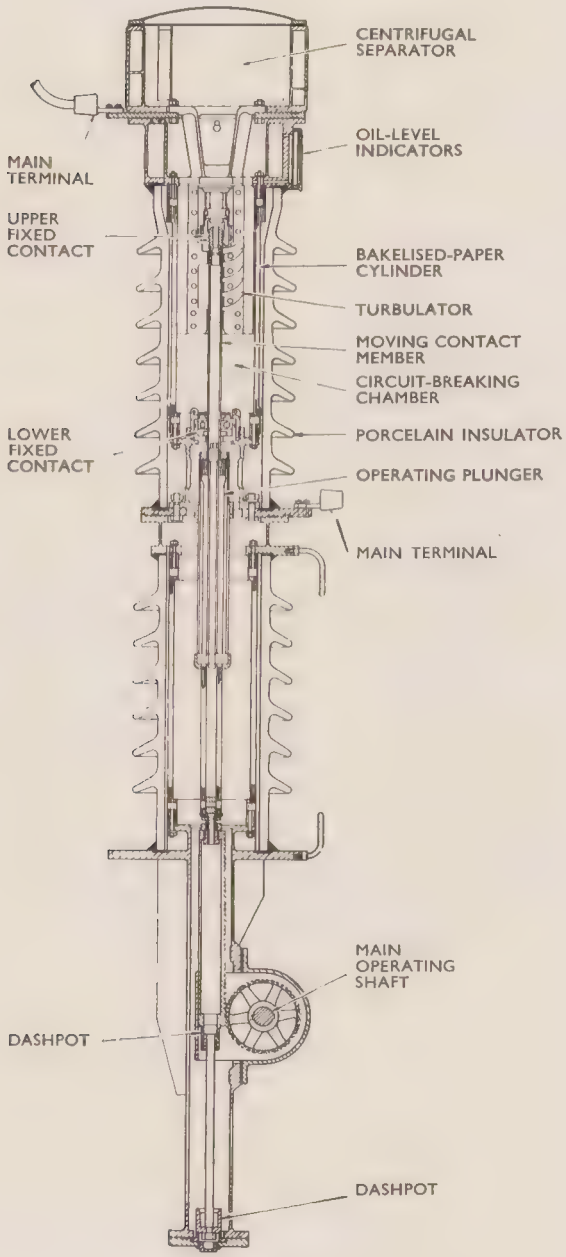


FIG. 9-12.
Cross-section of Single-phase Unit of Low-oil Content Circuit-Breaker (A. Reyrolle & Co., Ltd.).

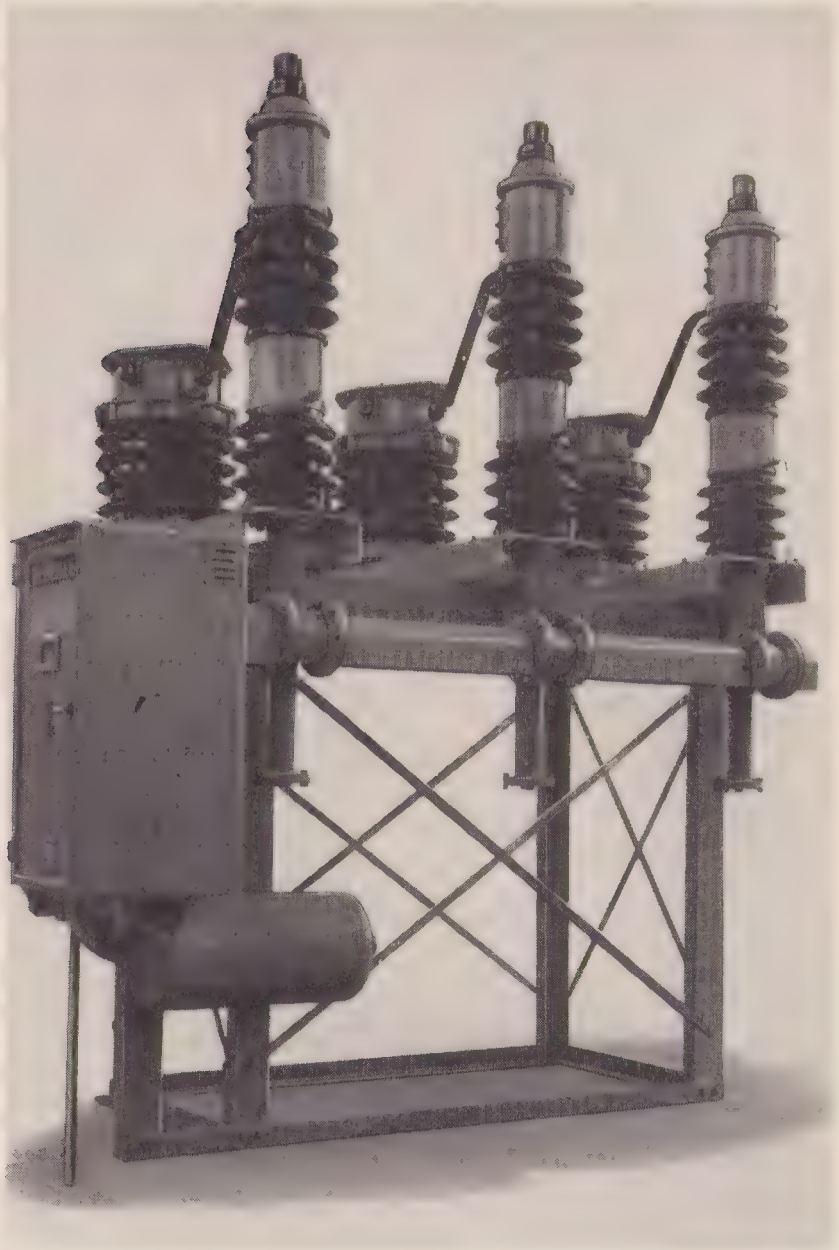


FIG. 9-13.
Low-oil Content Circuit-Breaker (A. Reyrolle & Co., Ltd.).

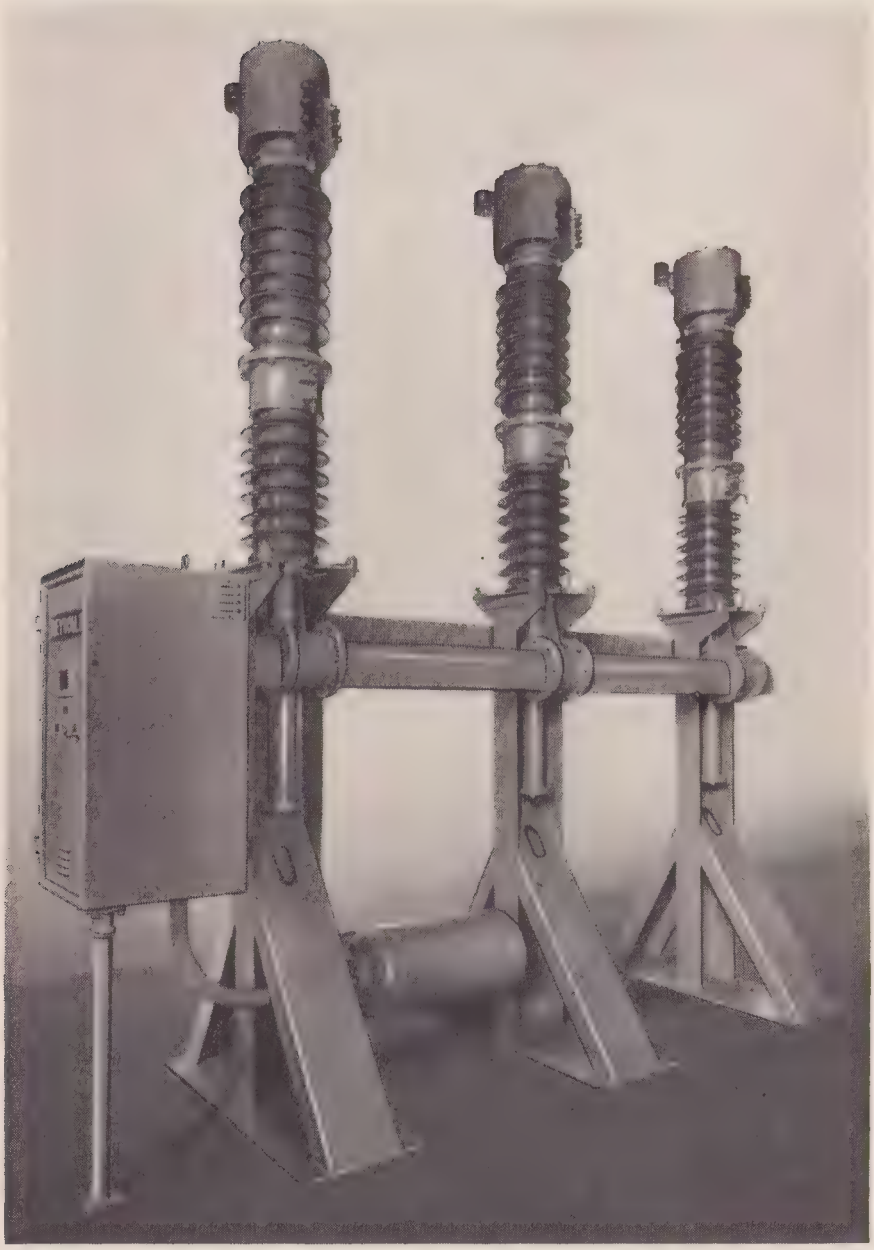


FIG. 9-14.
Low-oil Content Circuit-Breaker (A. Reyrolle & Co., Ltd.).

fingers is secured to the pot itself under spring pressure. When the pressure in the pot reaches the design figure, the back plate is forced away from the pot in such a way that an escape path is provided for the gases within the pot and automatically returns to position when the pressure is reduced.

Contact is maintained by the flexible connection from the pot to the back plate. Early tests showed that this modification was necessary to ensure satisfactory operation at values of short-circuit current of 5 per cent or less of the full rating.

The moving contact member is moved in a cross-head slide to ensure correct alignment into the baffle pot and into the fixed contacts to prevent any movement due to the short-circuit forces during operation. The circuit-breaker illustrated has a rating of 350 MVA at 11kV.

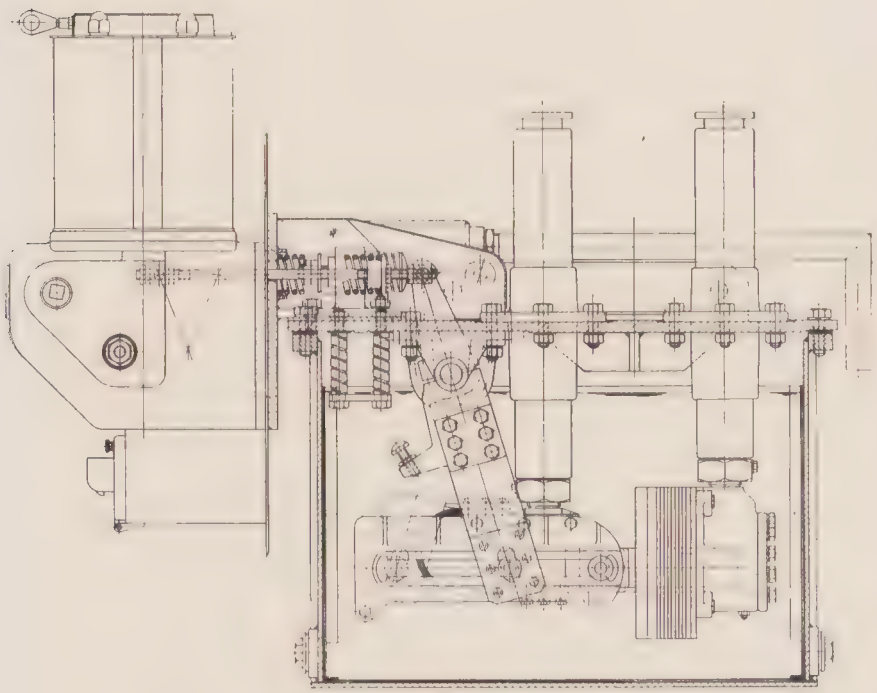


FIG. 9-15.—*Single-break Circuit-Breaker with Reduced Oil Content (Crompton Parkinson, Ltd.).*

By suitably shaping the moving contact member and the introduction of an arcing point, the arc is positioned most favourably near the vents for extinction.

In considering the use of low oil-content circuit-breakers it must be borne in mind that they are not suitable for frequent operation, the most severe example of which is electric furnace operation. This involves breaking a highly inductive load under conditions where the secondary of the transformer is virtually short-circuited due to failure of the arc to strike

in the furnace and this condition sometimes occurs several times on each melt. Records show that many hundreds of operations can arise in a week on this duty. Owing to the small quantity of oil, it rapidly carbonises, to such an extent that it will not remain fit for duty. The reduced oil-content

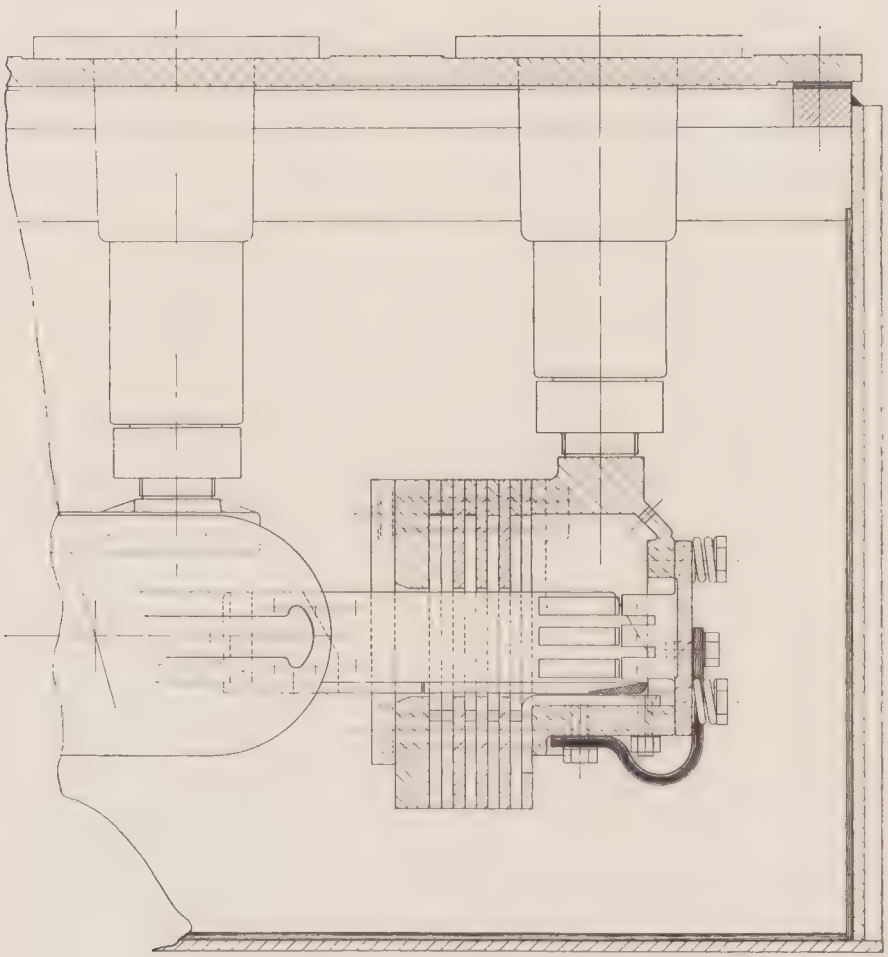


FIG. 9-16.—*Cross-section of Side-Baffle Arc Control Device as used in Fig. 9-15 (Crompton Parkinson, Ltd.).*

circuit-breaker overcomes this feature and ensures reasonable life before oil and contact renewal is necessary. The air-blast circuit-breaker described in the next chapter offers the best solution of all for frequent switching.

BIBLIOGRAPHY.

Switchgear Handbook, W. A. Coates and H. Pearce (Pitman and Sons).

Switchgear Practice, Arthur Arnold (Chapman and Hall).

"Safeguards against Interruption of Supply," H. W. Clothier, B. H. Leeson and H. Leyburn, "Journal I.E.E.," Vol. 82, No. 497, May, 1938.

"Progress in h.v. Metalclad Switchgear," D. R. Davies, "The Metropolitan-Vickers Gazette," April, 1941.

"Problems and Possibilities in Electrical Switchgear," H. Trencham, "B.T.H. Activities," Vol. 15, No. 5.

"The Development of the Single-Break Oil Circuit-Breaker for Metalclad Switchgear," D. R. Davies and C. H. Flurscheim, "Journal I.E.E.," 1936, Vol. 79, p. 129.

"Circuit Controlling Devices on Power Supply Systems (A Review of Progress)," C. W. Marshall, "Journal I.E.E.," April, 1942, Vol. 89, Part I, No. 16.

CHAPTER X

AIR-BLAST CIRCUIT-BREAKERS

In the preceding chapter, details have been given of low oil-content circuit-breakers. The development of these may be regarded as one stage in the endeavour to eliminate as far as possible the hazard of fire due to the use of oil. It has been stated that experience with British oil circuit-breakers, properly tested as they are, shows that they have not been the direct cause of many fires. Nevertheless, the fear exists and any development leading towards a reduction of this fear has been welcomed by users, particularly in the larger sizes of circuit-breaker where in normal oil-immersed designs many gallons of oil are necessary.

The development of low oil-content circuit-breakers is, then, one stage in this direction. The other stage has been the development of oil-less gear, in the form of the air-blast circuit-breaker.

Lest it be thought that the air-blast design removes all possible danger of fire or explosion, it is well to remind ourselves that risks still exist. In general, the air-blast circuit-breaker will be used in open-type structures, *i.e.*, cubicles, trucks, or stone cells. In any form of open-type switchgear, there is always a danger of arc-over in air, leading to explosions of a disastrous nature. Unless considerable care is exercised, the mere use of air-blast circuit-breakers will not remove this hazard and may indeed aggravate it, particularly as the exhaust gases may spread to the enclosure, leading to arcing. Hazards due to transient over-voltages will be referred to later.

Air-blast designs in Great Britain are relatively new. The reason for this is not far to seek—it lies in the fact that British designers made such a success of the conventional oil circuit-breaker that no urge was forthcoming to proceed at speed with the air-blast.

German designers, on the other hand, were faced with many oil circuit-breaker explosions in the period 1928-1930, and instead of perfecting this type turned to oil-less types. Because of this, Germany is often credited as being pioneers in this development, credit which in many ways is undeserved.

As long ago as the late 1890's crude designs of air-blast circuit-breakers were being toyed with in parallel with the oil breaker (also relatively crude in those early days) when the phenomena associated with arc interruption were very little understood. It so happened that this parallel seeking after improvement went ahead more rapidly in the oil-break design, with the result that air-blast took second place, although it was not dropped.

Nevertheless, as the demand for increased voltage and MVA ratings arose, so did users express concern at the large quantity of oil involved, coupled with the added difficulties of its maintenance. In Switzerland for example, considerable pioneer work was done in this respect mainly in the oil minimum or oil-less types.

In this country, research of a fundamental character was undertaken by the Electrical Research Association concerning the phenomena of breaking in oil which led to a study of breaking in air. This early fundamental

research culminated in many patents, one, a master patent, dating back to 1926. That development has been slow since that date is due, not so much to lack of interest or the conservatism of British designers, as to the difficulty of ensuring that air-blast circuit-breakers would be insensitive to circuit conditions. Much of the later research of the E.R.A. has been devoted to the problems of circuit severity, particularly those problems associated with the transient nature of the restriking voltage.

It is on the basis of this fundamental research, continuous over 20 years, that most British designs of to-day are based. As C. F. Winfield has stated in the discussion on A. R. Blandford's I.E.E. paper* : " I am glad to note that our designers are not running away from the problem of recovery voltage, as our Continental friends originally did, but are facing it."

In view of the success of British oil circuit-breakers, it is essential that any air-blast design should, apart from the elimination of oil and its maintenance, equal the oil breaker performance. Among the most important

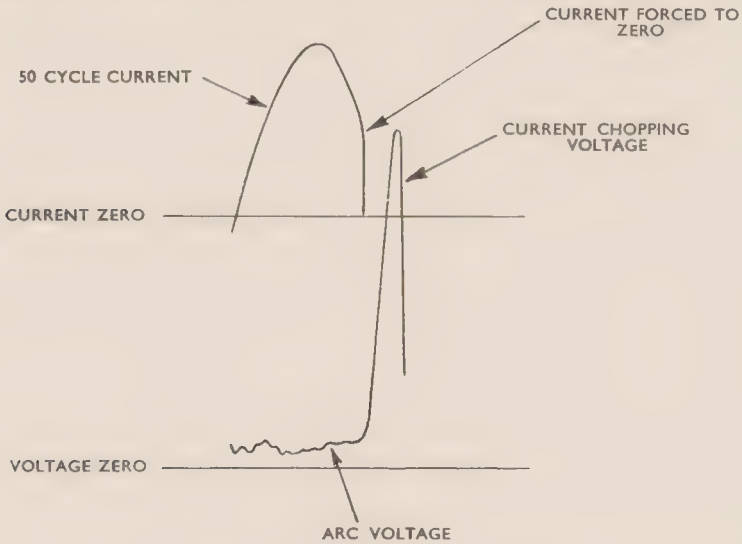


FIG. 10-1.

characteristics necessary are insulation security, adequate normal current carrying capacity, ability to operate rapidly at all values of current up to the short-circuit rating and at associated rates-of-rise of restriking voltage, there must be freedom from excessive over-voltages produced by the circuit-breaker itself, minimum erosion of contacts and accessibility to working parts for maintenance purposes. These are problems which designers have faced and have solved.

It is not within the province of a work of this nature to consider in detail the problems of circuit severity or over-voltages produced by the air-blast circuit-breaker itself. The general problem of severity is that of the transient nature of the restriking voltage and has been outlined in Chapter VII. Air-blast circuit-breakers have an inherent tendency to produce high restriking voltages and switching transients, owing to the short arcing time and the quick recovery of electric strength, arcing times

*See Bibliography.

of one half-cycle or less being commonly obtained. It has been shown elsewhere how this transient is determined by circuit characteristics and how it can be modified by the circuit-breaker itself. The problem of over-voltages produced by the circuit-breaker is one very similar to that experienced in the h.r.c. cartridge-type fuse in which "cut-off" occurs, *i.e.*, current is interrupted at a time other than at one of the natural zero pauses. This is known as current chopping (see Fig. 10-1) and is evidenced where an air-blast circuit-breaker is dealing with low values of current such as transformer magnetising currents and line charging currents.

Cox and Wilcox* have stated that "as the 50-cycle current being interrupted approaches zero, a value is reached at which de-ionisation of the arc in the contact gap is so rapid that the current is forcibly suppressed before the natural zero point."

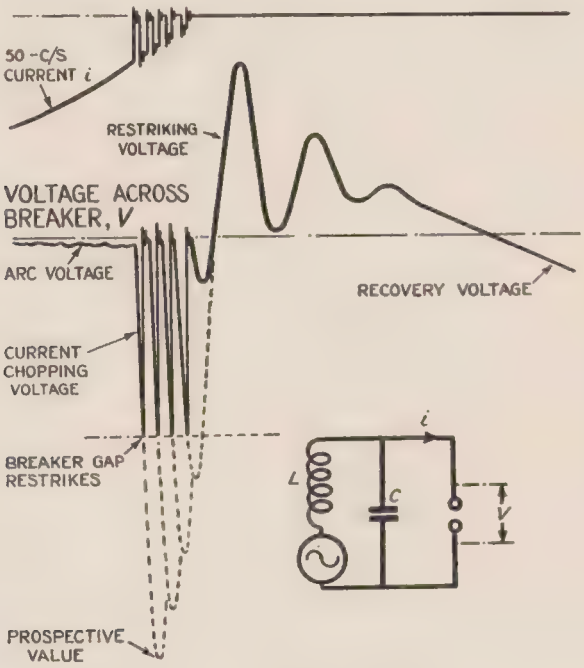


FIG. 10-2.—(*Journal I.E.E.*)

"If the total reactance of the circuit is such that the current to be interrupted is of the order of 150 amp. r.m.s. or above, this forcible suppression occurs when the current has nearly reached its normal zero. With higher values of circuit reactance giving lower values of 50-cycle current, the total amount of ionisation of the contact gap is less and suppression of the current occurs earlier before the normal current zero at a higher instantaneous value, thereby inducing a higher voltage in the increased circuit inductance. With a correctly designed breaker this voltage is prevented from rising to a dangerous value by breaking down the contact gap and re-establishing the normal arc. The arc current which flows is again forcibly suppressed and the process is repeated until the current almost reaches its normal zero, as shown in Fig. 10-2."

**See Bibliography.*

The voltage generated due to current chopping may have a value several times the insulation level of standard apparatus and unless limitation is imposed by restriking of the contact gap as described by Cox and Wilcox, there will be limitation by failure of external insulation. Not only does current suppression cause voltages to earth but it also induces local voltages in individual pieces of inductive apparatus.

These problems have been studied in greater detail by various investigators and they have published their findings in learned papers, some of which are noted in the bibliography. Suffice it here to note that the air-blast circuit-breaker is particularly sensitive to circuit severity and that the design is prone to current chopping in a way not experienced to any great extent in the oil circuit-breaker, this being due to the fact that the de-ionising agent is available in full at *all* values of current, whereas the opposite is true in the oil breaker.

Whereas current chopping can only be taken care of in the design of the circuit-breaker, the sensibility of the circuit-breaker to restriking voltage

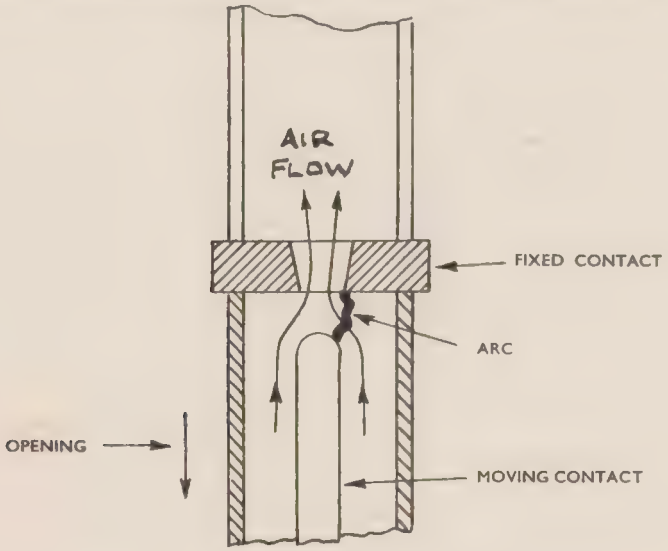
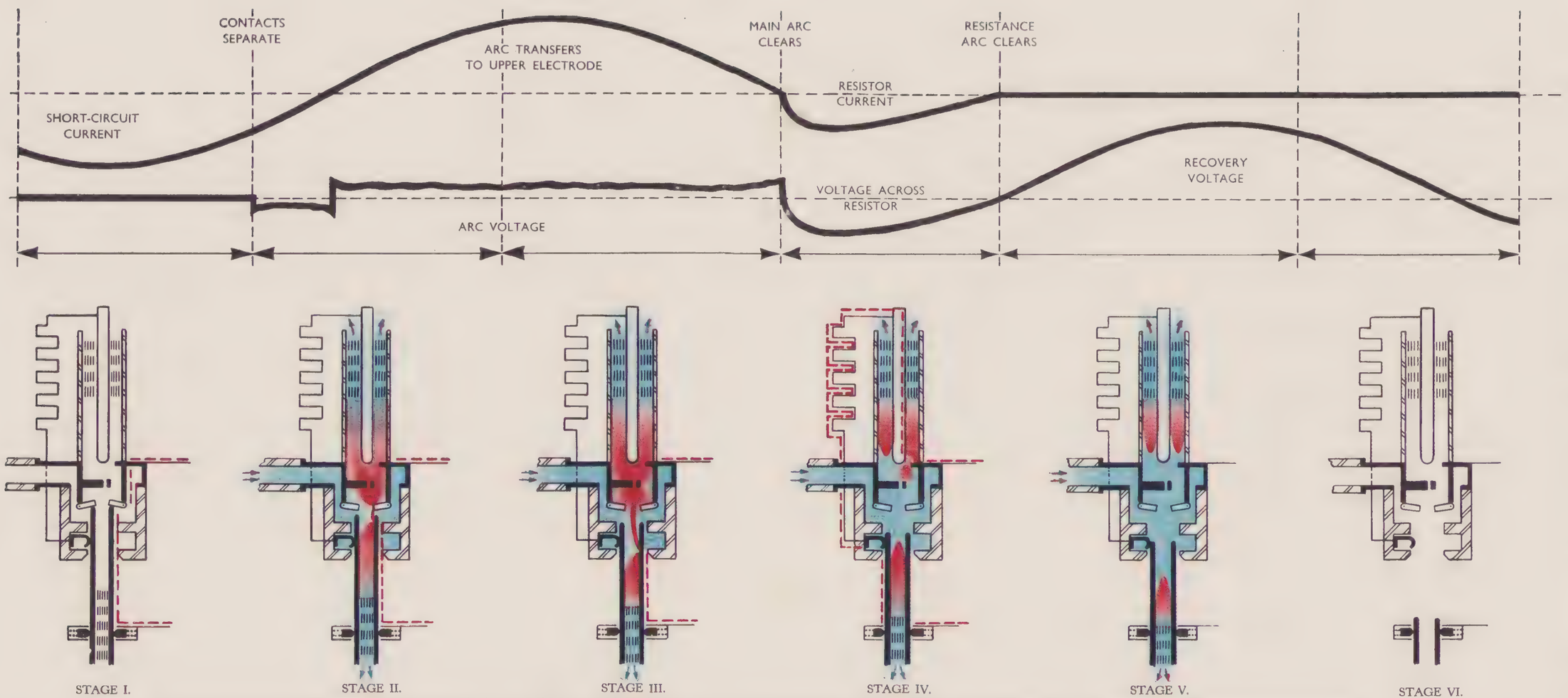


FIG. 10-4.
Principle of Axial-Blast Air Circuit-Breaker.

can be modified by the use of resistance switching. The exponents of this claim that the performance of the breaker is made almost entirely independent of the inherent restriking voltage transient of any circuit on which it may be used. Resistance switching involves the use of external resistances connected to shunt the main contact gap and which are automatically connected in the circuit by the arc transferring to a probe. The operation can best be described by illustration and Fig. 10-3 shows the complete process of current interruption by means of resistance switching as arranged in a design by The British Thomson-Houston Co., Ltd.

Not all air-blast circuit-breakers incorporate resistance switching. It is usual in the design known as axial-blast (designs of this type do exist without resistance switching) and is less frequently used in the design known as cross-blast.



This illustration shows the complete process of current interruption by means of resistance switching from the time of tripping the breaker until the circuit is finally interrupted and full voltage is established across the breaker terminals.

FIG. 10-3.—*Principle of Current Interruption in "Aeroblast" Circuit-Breakers (The British Thomson-Houston Co., Ltd.).*

the moving contact by an auxiliary sliding contact. The other end of the resistor is connected to a probe which is insulated from the stationary contact by a short air gap.

STAGE II.

The breaker has received a trip impulse and compressed air is admitted to the blast head. When full pressure is attained in the blast head, the opening cylinder causes the moving contact to retract, and an arc carrying the fault current is drawn between the tip of the moving contact and the ends of the stationary contact segments. The compressed air in the blast head then escapes upwards through the orifice formed in the centre of the segmental contacts and is exhausted to atmosphere through the vent tube and cooling fins. A downward blast of air also flows through the hollow moving contact and impinges on cooling fins before escaping to atmosphere. The arc is thus subjected to a high velocity stream of air which flows radially inwards and then divides and flows in opposite directions to escape through the upper and lower nozzles.

STAGE III.

The upward blast of the double stream has swept the arc root away from the segmental contacts and transferred it to auxiliary arcing electrodes. The arc root is thus quickly transferred away from the segmental contacts which carry the normal load current and burning of the contact surfaces is reduced to a minimum. A patented construction of the auxiliary arcing electrodes causes the arc root to rotate at a high speed and so minimize burning of the electrodes. A somewhat similar effect occurs on the moving contact, but in this case the air stream sweeps the lower arc root down the inside of the hollow tube as shown in the illustration. As the arc is forced further down the tube, the volt drop across the arc increases until it shorts itself by striking across to the mouth of the tube. This process is repeated rapidly and the movement of the arc prevents the formation of a hot cathode spot and so reduces the burning of the contact.

STAGE IV.

The moving contact has now opened far enough for the arc to be interrupted at a current zero, and the re-striking voltage transient appears across the contact gap and also across the probe gap. At this instant, the main contact gap is being fed with cool air at full pressure, while the probe gap is still bridged with hot ionized air escaping from the arc region and having a much lower dielectric strength. The probe gap therefore arcs over and the resistor is thus shunted across the main contact gap. The rate at which the voltage across the contact gap can rise is now limited to the rate at which current can rise through the resistor and system inductance in series. The ohmic value of the resistor is chosen so that the natural transient oscillation of the circuit is completely damped at currents approximating the breaking capacity of the breaker, and the voltage across the contact gap therefore rises exponentially to the normal 50 cycle peak value.

STAGE V.

While current is flowing through the resistor, the power factor of the circuit approaches unity, so that when the resistor current is interrupted at the next current zero the recovery voltage is also at or near zero. The small resistor current is thus easily interrupted by the comparatively low-pressure stream of air and the normal recovery voltage appears across the breaker terminals. The air supply to the blast head is then cut off, but the moving contact continues to retract and breaks contact with the auxiliary sliding contact. The resistor is thus isolated from both terminals of the breaker.

STAGE VI.

The pressure in the blast head has now fallen to atmospheric value and the moving contact is in the fully open position.

The essential difference between these two types is that in the former, the air stream is in line with the arc and envelopes the moving (male) contact as it parts from the segmental (female) contact. This is shown in Fig. 10-4. In the cross-blast design, the air stream is directed at right angles to the arc, and by means of an arc chute, is lengthened and cut into what may be regarded as a series of short arcs. This is shown in Fig. 10-5.

In the axial-blast design, movement of the contact rod is limited to a few millimetres and is automatically opened by the pressure of the air. It demands therefore a means of isolation from the circuit, and this is provided by a separate isolator which opens after the arc has been interrupted on the main contacts or at such a time when in opening, it has only to deal with the resistance current.

This involves close timing of operating valves and, what is more important, an isolator able to close at high speed as the operation of closing on to a circuit is finally accomplished on this isolator, which therefore, has the onerous task of satisfying the " making-capacity " test.

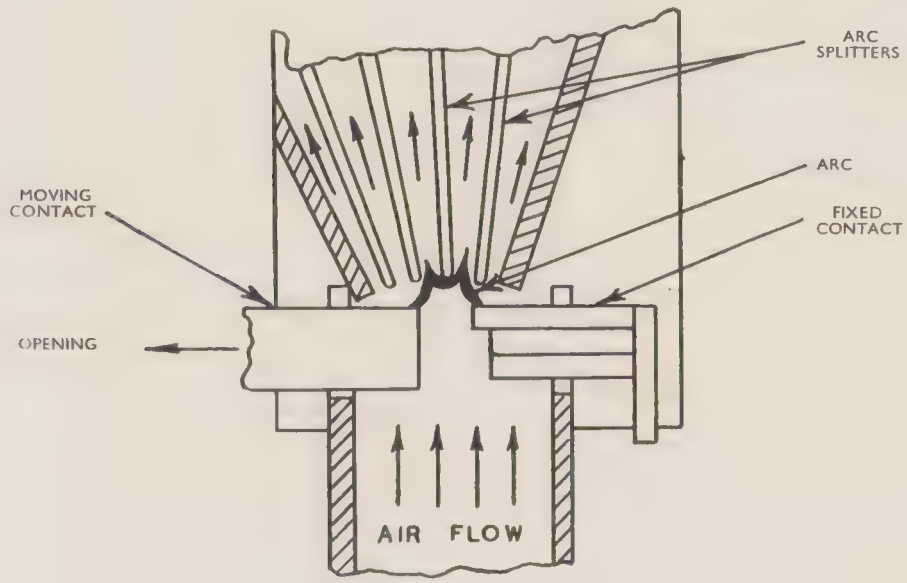


FIG. 10-5.
Principle of Cross-blast Air Circuit-Breaker.

In opening, the main contact moves under air pressure against a spring and once the air pressure is removed, recloses.

The foregoing is shown in Fig. 10-6.

In the cross-blast design, a moving contact arm operates in close proximity to an arc chute to draw an arc which is forced by the air blast on to splitter plates which cause a lengthening of the arc as shown in Fig. 10-5.

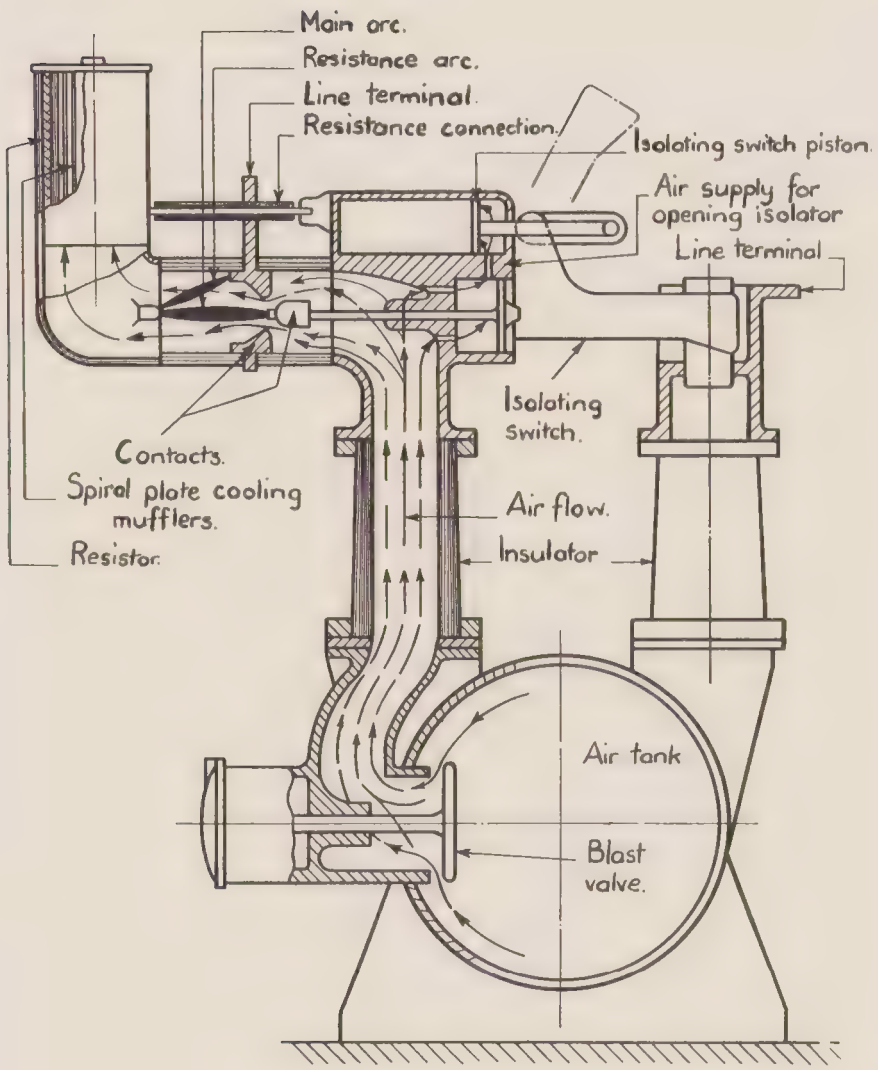


FIG. 10-6.—*Principle of Axial or Radial-Blast Circuit-Breaker (English Electric Co., Ltd.).*

The movement of the contact arm in this case is such as to provide full isolation without the need for a separate isolator as in the axial blast (see Fig. 10-7).

It has been stated that in the cross-blast design, resistance switching is only infrequently resorted to. This is because in lengthening the arc without undue restriction, sufficient resistance is automatically introduced in the arc itself to control the restriking transient. Where resistance switching is resorted to, the resistance may be connected in sections across the splitters. Here, the value of resistance introduced depends on how many sections of the arc chute are brought into use, *i.e.*, whether a long or short arc is drawn.

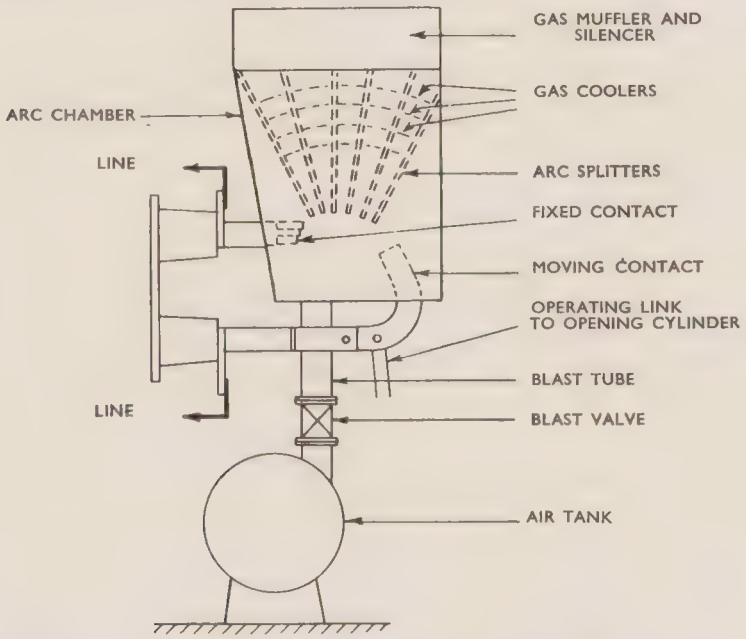


FIG. 10-7.—*Outline of Cross-Blast Circuit-Breaker.*

Before describing typical British designs it may be well to briefly enumerate advantages of air-blast gear other than the elimination of oil. These may be summarised as follows :—

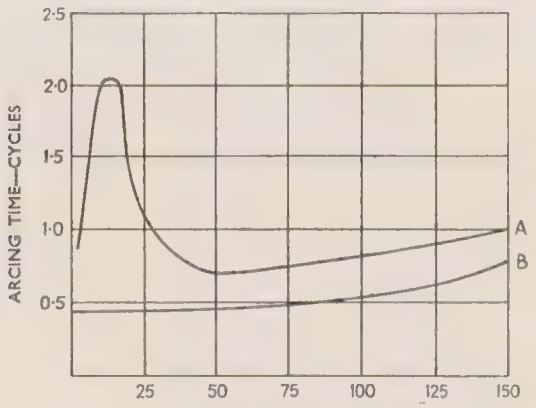
(1) High speed operation.
(2) Short and consistent arc duration.
(3) Ability to withstand very frequent operation, as in furnace control.
(4) Facility for high speed reclosing.
(5) Very considerably reduced maintenance.

Each of the foregoing is important. As to (1), this is generally desired on large intercommunication systems in order to maintain stability. In general, *total* break times of the order of 3 to 4 cycles are attainable with air-blast circuit-breakers, an achievement which involves considerable complication in the conventional oil-break design.

As to (2), it is well known that in the oil circuit-breaker, fitted with arc control devices, arcing times are not consistent to the same degree throughout the range of current interrupted. Fig. 10-8 shows at curve A the general performance at various values of interrupting capacity. The relatively large jump in arcing times at low values is noted. (See also Chapter VIII.) Curve B illustrates the average performance expected in air-blast designs and illustrates consistent performance over a range.

Advantage (3) is possible due to the absence of oil and the consequences of repeated arcing and deterioration, and to the lower wear and tear on the interrupting elements.

The growing requirement for rapid reclosure (4) applies more particularly to high voltage interconnected networks and is more easily achieved in the shortest times, of the order of 10-20 cycles, with the air-blast type of breaker.



Current interrupted %

A = Oil Break.

B = Air Blast.

FIG. 10-8.

This is on account of the low inertia of the interrupting elements and the relative ease with which compressed air mechanisms can be reversed, as compared with the solenoid-operated mechanisms normally used with large oil circuit-breakers.

Rapid interruption with short arcing times leads to reduced maintenance (5) coupled with the complete elimination of oil maintenance.

In the cross-blast type some maintenance is essential on the interrupter assembly, due to erosion of destructible material in the arc chute. This, however, is slight compared with the maintenance essential for the normal oil circuit-breaker.

Against the advantages set out above, there are several features which must offset them. Chief among these is the maintenance and upkeep of the compressor plant, the possibility of the loss of air rendering the equipment inoperative, the general unsuitability of air blast circuit-breakers to house bushing type current transformers (as in high-voltage oil circuit-breakers) involving separate oil immersed or compound filled current transformers,

and the problems associated with air pipe lines, fittings, etc., with the almost inevitable leakages. A further disadvantage (if it may be so termed) is the general unsuitability of axial air-blast circuit-breakers for incorporation in metalclad switchgear constructions which have become so popular in Great Britain. This is particularly true with the axial blast type due mainly to the need for a separate isolator. It does not apply to the cross-blast type (see discussion on A. R. Blandford's I.E.E. paper by J. Christie and D. R. Davies).

Very largely, development in Great Britain in air-blast circuit-breakers has been more pronounced for the higher voltages, *i.e.*, 33 kV and above, and more particularly for the extra high voltages of 110, 132 and 264 kV with interrupting capacities up to 3,500 MVA, where the saving in space, weight and oil content is greatest. Even so, many equipments have been developed introducing the type of circuit-breaker for use on 6·6, 11 and 22 kV systems with interrupting capacities of 250, 350 and 500 MVA. What follows will serve to indicate the progress of development by various makers up to the time of the preparation of this volume.

The British Thomson-Houston Co. Ltd., have introduced two distinct types. One, designated "Aeroblast," covers the voltage range 6·6 kV to 33 kV and has interrupting capacities up to 750 MVA at 6·6 and 11 kV, and 1,000 MVA at 33 kV. The second designated "Aerojet," covers the voltage range 66, 132 and 264 kV, for interrupting capacities of 1,500, 2,500 and 3,500 MVA respectively. In the "Aeroblast" design, resistance switching is incorporated and the general theory of its operation is that shown earlier in Fig. 10-3, where it has been noted that the circuit-breakers are arranged to interrupt both the resistance shunted arc and the subsequent unshunted arc in a single-blast head utilizing the same blast of air for both functions.

This feature distinguishes the "Aeroblast" from the "Aerojet" circuit-breakers, which have two blast heads per phase, one to interrupt the shunted arc and the other the unshunted arc.

A cross section of a typical "Aeroblast" circuit-breaker is shown in Fig. 10-9. This, together with Fig. 10-3, indicates that the design is a modified form of radial blast breaker, and that no separate isolator is required because the moving contact moves to a distance sufficient to complete electrical isolation. The pneumatic operation of this type of circuit-breaker is illustrated in Fig. 10-10. In a closing operation, the blast valve remains closed and the circuit is made on the contacts in air at atmospheric pressure. The slight pre-arcing which takes place before the contacts is confined within the blast head and is quite innocuous. The moving contact is lifted by the insulation operating arm which is driven by the piston in the closing cylinder. When the contact is fully closed, it is held in position by a prop which engages with a roller fixed to the end of the operating arm.

The closing coil operates the closing valve by means of a beam which is pivoted at one end.

There are two ports in the closing valve, one of which is normally held closed by the pressure in the receiver, while the other is open to atmosphere. Energising the closing coil simultaneously closes the atmospheric valve and opens the pressure valve, allowing air to flow from the air receiver to the closing cylinder. When the breaker is fully closed, the closing coil circuit is broken by an auxiliary switch driven from the main shaft. The air supply to the closing cylinder is cut off and the air which remains in the closing cylinder escapes to atmosphere through the atmospheric valve.

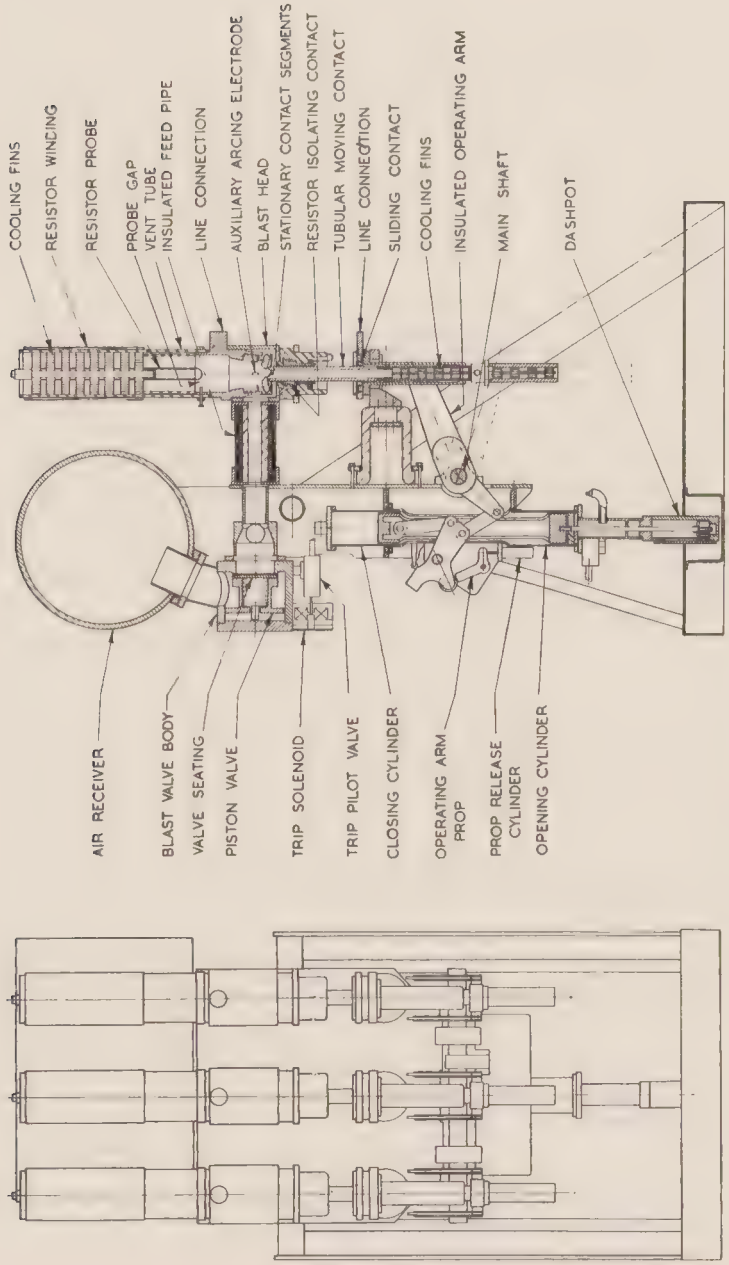


FIG. 10-9.—*Front and Sectional Views of "Aeroblast" Circuit-Breaker (The British Thomson-Houston Co., Ltd.).*

The opening operation of any air-blast circuit-breaker demands one fundamental requirement to be fulfilled, namely that the contact must not open until the required pressure for arc interruption is present in the blast head. In the " Aeroblast " design the pressure which builds up in the blast head operates a valve which in turn admits air to the opening cylinder, thus ensuring correct sequence of operation. This sequence is as follows (see Fig. 10-10).

The trip pilot valve is opened by energising the trip coil and air at the back of the blast servo valve piston escapes to atmosphere. The front of this piston is subjected to the full receiver pressure, but only over an area

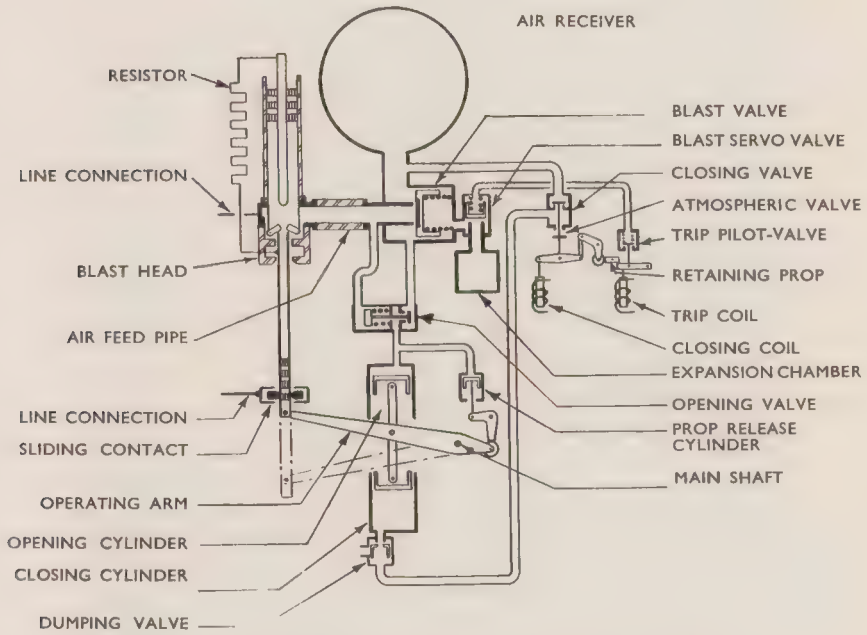


FIG. 10-10.—*Pneumatic operation of "Aeroblast" Circuit-Breaker (The British Thomson-Houston Co., Ltd.).*

equal to one half the area of the back of the piston. When the pressure on the back has fallen to less than half the receiver pressure, the piston valve retracts from its seating and opens the blast servo valve. The main blast valve is then exhausted through the servo valve, but instead of exhausting straight to atmosphere, it exhausts into an expansion chamber. The main blast valve now opens and pressure builds up in the blast head and also in a cylinder containing a spring-loaded piston attached to the opening valve.

When the correct pressure is reached, the opening valve admits air to the prop-release cylinder and also to the opening cylinder and the breaker starts to open. After the arc is extinguished and the moving contact is about to leave the blast head, the pressure in the expansion chamber on the servo valve has built up to the full receiver pressure and the main blast valve closes. The opening valve, which has a delay action, remains open until the contact has completed its travel.

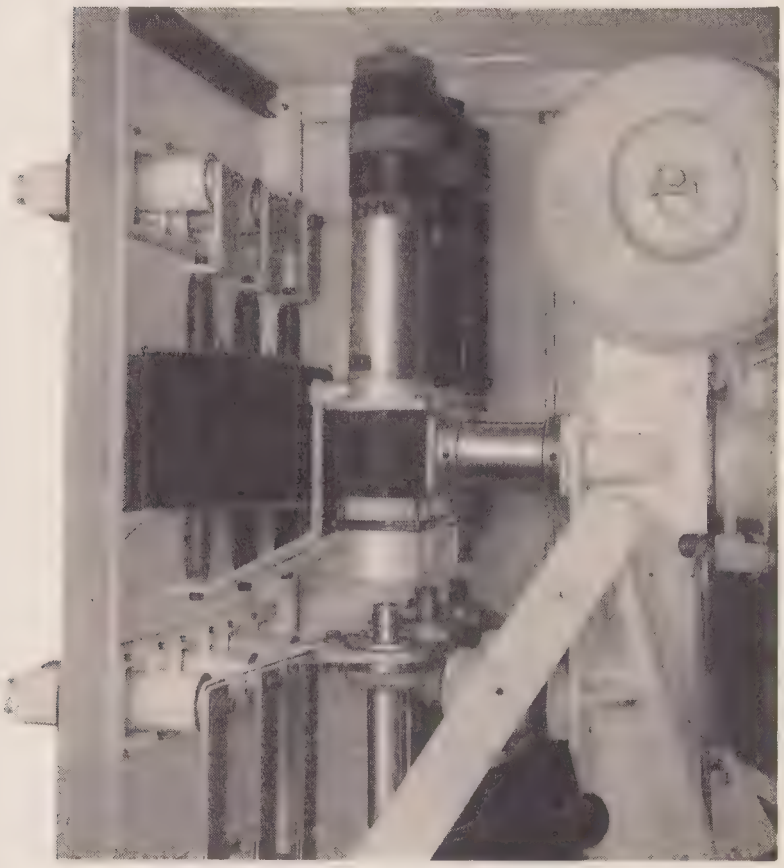


FIG. 10-11.—*" Aeroblast " Circuit-Breaker in Truck Type Cubicle (The British Thomson-Houston Co., Ltd.).*

When closing on to a fault, a circuit-breaker must open again immediately the trip coil is energised. When such a tripping impulse is received, it will be noted that the closing valve is still open and the closing cylinder is charged at full pressure.

It is therefore necessary to cut-off the air supply to the closing cylinder and also to exhaust the closing cylinder to atmosphere so quickly that the opening of the breaker is not delayed. This is accomplished by a valve inter-tripping mechanism in conjunction with a dumping valve.

Fig. 10-11 illustrates an " Aeroblast " circuit-breaker mounted in a truck cubicle. This is a close-up to show the circuit-breaker. Busbars (single or duplicate) are accommodated in the fixed portion of the truck at the bottom, *i.e.*, at a lower level than the breaker. This arrangement, which is the reverse of the normal arrangement utilising an oil breaker, permits the exhaust muffler and cooler to be high in the truck at a point where the exhaust gases may be safely expanded and dispensed.

In the B.T.H. Co., Ltd. "Aerojet " design, which is used at the higher voltages, interruption is carried out by means of a blast of compressed air passing through one or more radial blast nozzles. These nozzles comprise two mushroom-shaped hollow contacts which are normally pressed into contact by a spring, but are forced apart by the compressed air so long as the blast valve remains open.

They close again immediately the blast valve closes, and a series air-break isolator incorporated in the breaker mechanism opens after the main current is broken on the nozzles. A number of blast heads may be arranged in series, the number chosen being determined by the combination of voltage and breaking capacity rating.

Three types are available, one without resistance switching, in which satisfactory performance is obtained by the blast head alone, and two with resistance switching. The latter have (*a*) resistances of the non-linear type or (*b*) of the linear type.

This range of circuit-breakers has the following ratings :—

1,500 MVA at 66 kV.
2,500 MVA at 132 kV.
3,500 MVA at 264 kV.

A typical single-phase unit for 132 kV service is shown in Fig. 10-12.

This type of air-blast circuit-breaker has been considered in detail in the paper by Cox and Wilcox*.

The General Electric Co. Ltd., have developed a design of cross-blast circuit-breaker having a rating of 750 MVA at 11 kV. The arc is interrupted by being blown into an arc chute of insulating material; the arc chutes together with the fixed contacts of the breaker are contained in the box-like structure at the top of the truck in Fig. 10-13.

The moving contacts, of L shape, are pivoted in bearings carried by insulators supported from the air tank and pass through slots in the lower ends of the chutes to engage with the fixed contacts. The insulating pipes carrying the air blast enter the chutes at the lower end and the gases from the arc, after having been cooled by internal coolers, emerge at the upper end of the front edge of the arc chute.

The moving contacts and the blast valves are operated by levers keyed to a main shaft which in turn is driven by an air engine. Damping resistances are provided which make the operation of the breaker independent of considerable variations of the inherent rate of rise of the restriking voltage.

* *See Bibliography.*

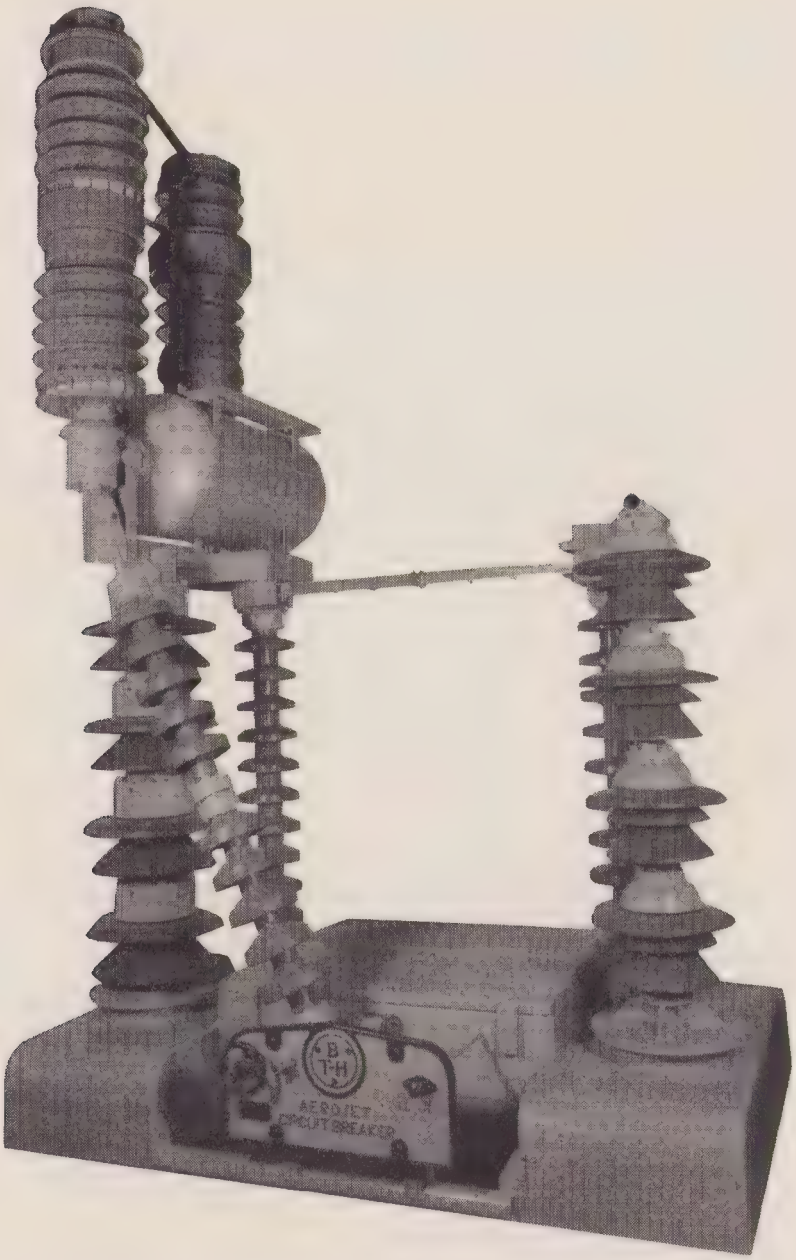


FIG. 10-12.—132 *kV "Aerojet" Circuit-Breaker (The British Thomson-Houston Co., Ltd.).*

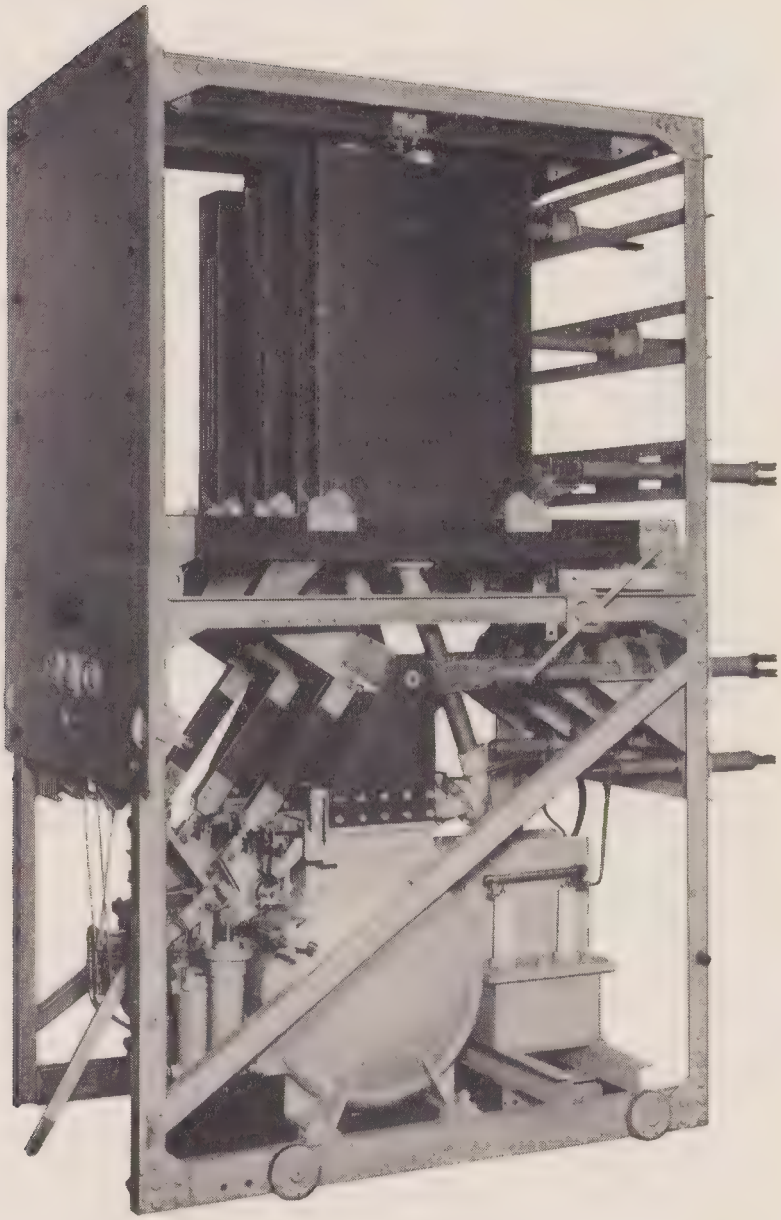


FIG. 10-13.—*Cross-blast Circuit-Breaker in Truck Type Cubicle (The General Electric Co., Ltd.).*

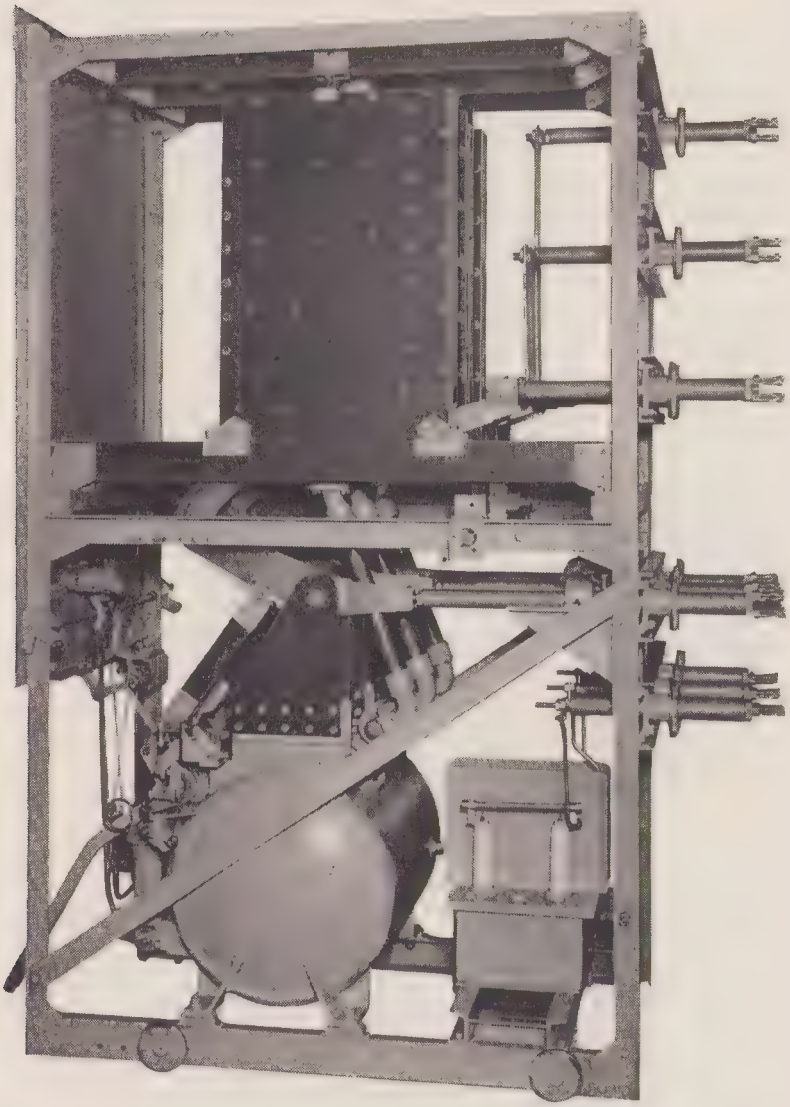


FIG. 10-14.—11 *kV Cross-blast Circuit-Breaker in Truck Type Cubicle (The General Electric Co., Ltd.).*

The circuit-breaker is mounted in a truck, as shown in Figs. 10-13 and 10-14, which in turn is accommodated in a stone cell, at the back of which are further cells containing the busbars and cable boxes.

Messrs. Ferguson, Pailin, Ltd., have a range of air-blast circuit-breakers for voltages of 33 kV and upwards. In the 33 kV class, an indoor type as shown in Fig. 10-15 is available for mounting in cubicle type structures. This is of the axial blast type in which one of the vertically mounted insulators of each phase carries the interrupter head which is complete with retractable contact, nozzle, resistance and exhaust head. The other vertically mounted insulator forms a support for the fixed contact of the series isolator.

The retractable contacts operate vertically when the compressed air is introduced to the interrupter head by the operation of a main blast valve and the outlet air blast is led through a vertical silencer to exhaust to atmosphere. The exhaust tube is fitted with cooling stacks which cool and de-ionise the gas and diminish the audible disturbance. The action of the interrupter head is such that one of the arc roots is caused to transfer to the tip of a steel probe and a resistance is thereby introduced into the main circuit. The series isolators are operated automatically during the opening action of the circuit-breaker and are carefully timed to ensure that they do not commence to open until arcing has ceased in the interrupter head.

As Fig. 10-15 indicates, the three phases are mounted on a common framework and air supply reservoir. The 33 kV circuit-breaker has a rating of 750 MVA.

For voltages of 66 kV and above, Messrs. Ferguson, Pailin, Ltd. have developed what is known as a " Duo-Blast " Circuit-breaker. The principle of its operation is shown in Fig. 10-16. In place of the solid retractable contact used in a single nozzle design, two hollow nozzles are provided. The operation of the tripping valve of the circuit-breaker introduces air supply to the interrupting head and thus forces the two nozzles to separate. After separation of the contacts the flowing air exhausts equally through each nozzle, thereby subjecting the arc products to both radial flow and axial flow conditions. The scavenging action is considerably intensified by the divided blast, whilst both arc roots are initiated in a zone of high velocity outflowing air. A feature of the design is the rapid transfer of the arc roots to points on the downstream side of the nozzles, thus effectively reducing the quantity of metal vapour drawn into the arc zone, as shown in Fig. 10-17 (A). This advantage is not obtained by the use of two single nozzles in series as shown in Fig. 10-17 (B), where elimination of the metal vapour in the gap is only possible from two of the four arc roots.

A 3-phase 132 kV outdoor circuit-breaker is shown in Fig. 10-18. Each phase comprises two main vertical porcelain insulator pillars, at the top of which is an interrupter head. Each supporting pillar houses a glazed porcelain inlet pipe supplying air to the interrupter head, the latter being complete with retractable upper nozzle contact, fixed lower nozzle contact, arc probes, and exhaust ports. The isolator blade of each single phase moves in a vertical plane and is operated by a vertical porcelain tortional drive, the operating mechanism being at earth potential. The isolator blade is connected to the lower end of one of the interrupter heads and the isolator fixed contact is connected to the upper end of the other interrupter head.

The fixed and moving contacts of a typical interrupter head are shown in Fig. 10-19.

A 3-phase 66 kV outdoor circuit-breaker is shown in Fig. 10-20. This has only one interrupter head mounted on one of the supporting pillars.

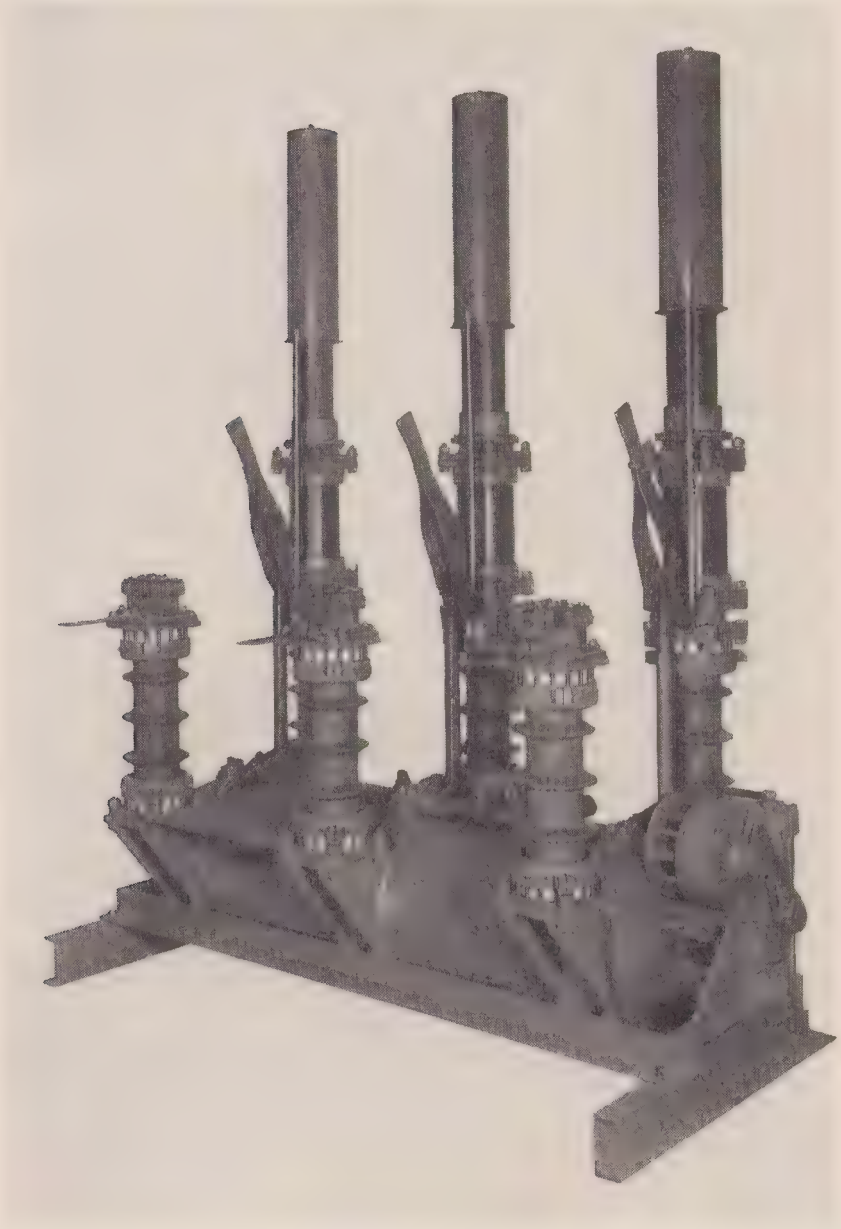


FIG. 10-15.—*Axial-blast Indoor Circuit-Breaker 33kV (Ferguson, Pailin, Ltd.).*

The other pillar may house a current transformer or may only support the fixed contact of the isolator. The interrupter head is similar to that described for 132 kV.

Both breakers have an air reservoir forming the base of a single phase equipment.

The 132 kV circuit-breaker has a rating of 1,500 MVA at full test plant severity. Where the severity is reduced, as in normal service conditions, the rating can be increased to 2,500 MVA. The 66 kV circuit-breaker is rated at 750 MVA.

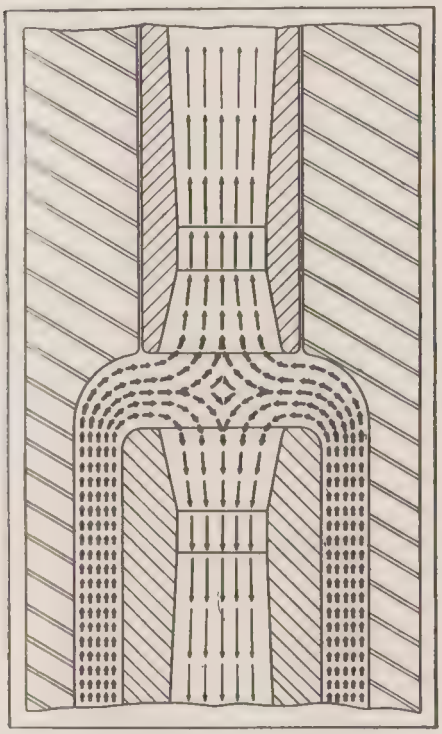


FIG. 10-16.—*Principle of Duo-Blast Circuit-Breaker (Ferguson, Pailin, Ltd.).*

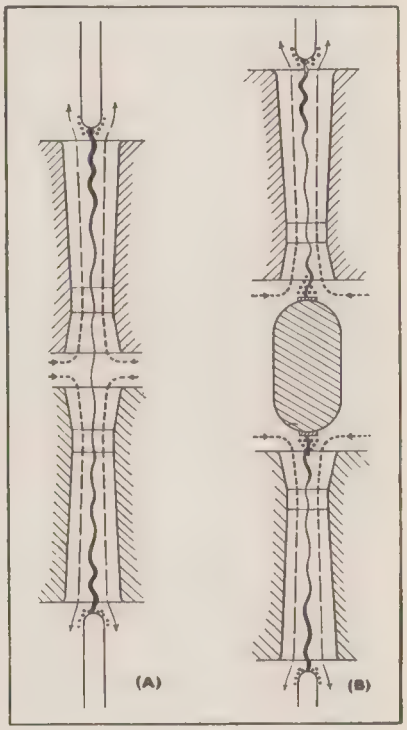


FIG. 10-17.

Messrs. A. Reyrolle and Co., Ltd., have developed a range for voltages of 66, 110 and 132 kV (see Figs. 10-24 and 10-25), and have designs available for higher voltages up to 264 kV. These designs incorporate what is described as single or duplex air blast turbulators constituting the arc control and arc extinguishing devices. The characteristics of the design are; all metal construction eliminating all solid insulation from the proximity of the arc; the division of the contact assembly into current-carrying contacts, arc initiating contacts and fixed arcing electrodes; inclusion of means of limiting restriking voltage.

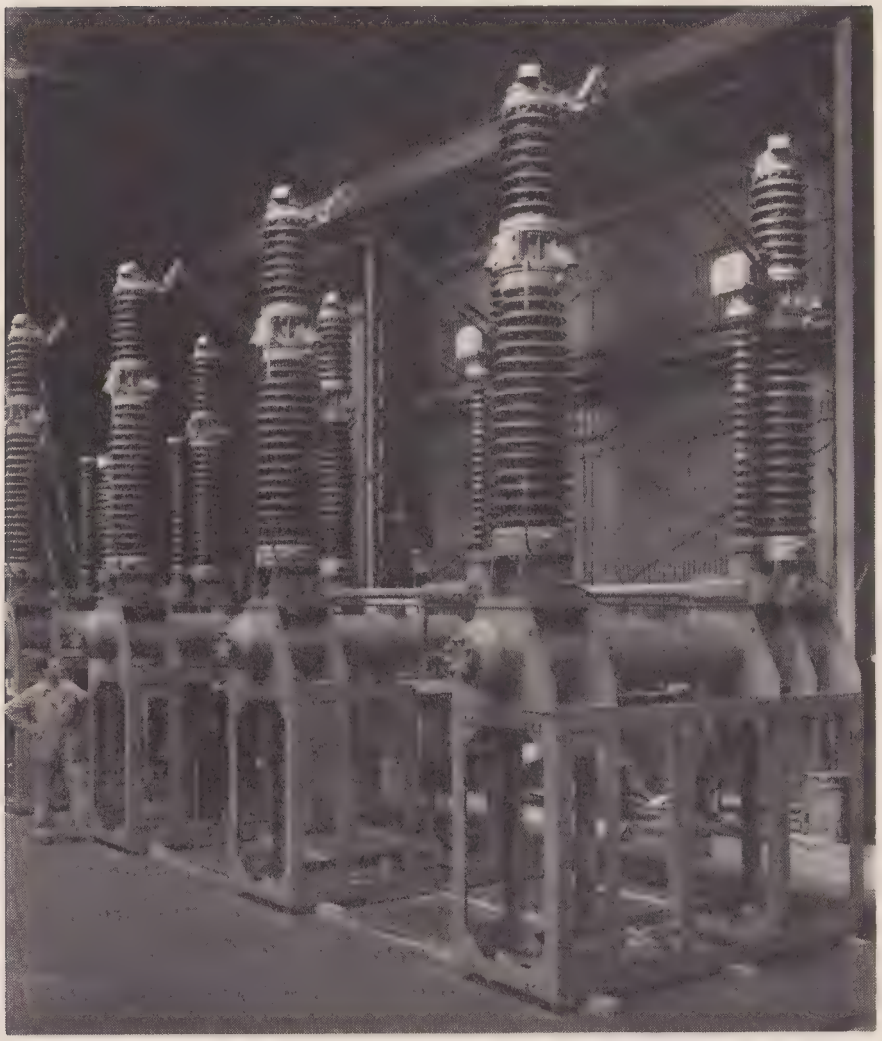


FIG. 10-18.—132 kV *Duo-Blast Circuit-Breaker*
(Ferguson, Pailin, Ltd.).

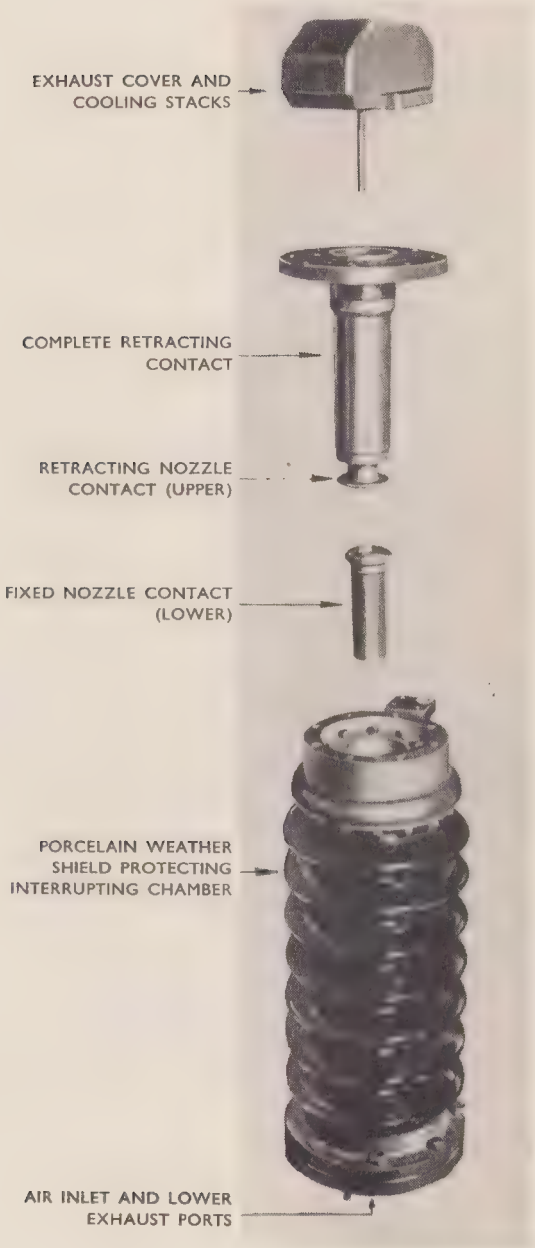

EXHAUST COVER AND COOLING STACKS
COMPLETE RETRACTING CONTACT
RETRACTING NOZZLE CONTACT (UPPER)
FIXED NOZZLE CONTACT (LOWER)
PORCELAIN WEATHER SHIELD PROTECTING INTERRUPTING CHAMBER
AIR INLET AND LOWER EXHAUST PORTS

FIG. 10-19.—*Fixed and moving contacts of a typical interrupter head (Ferguson, Pailin, Ltd.).*

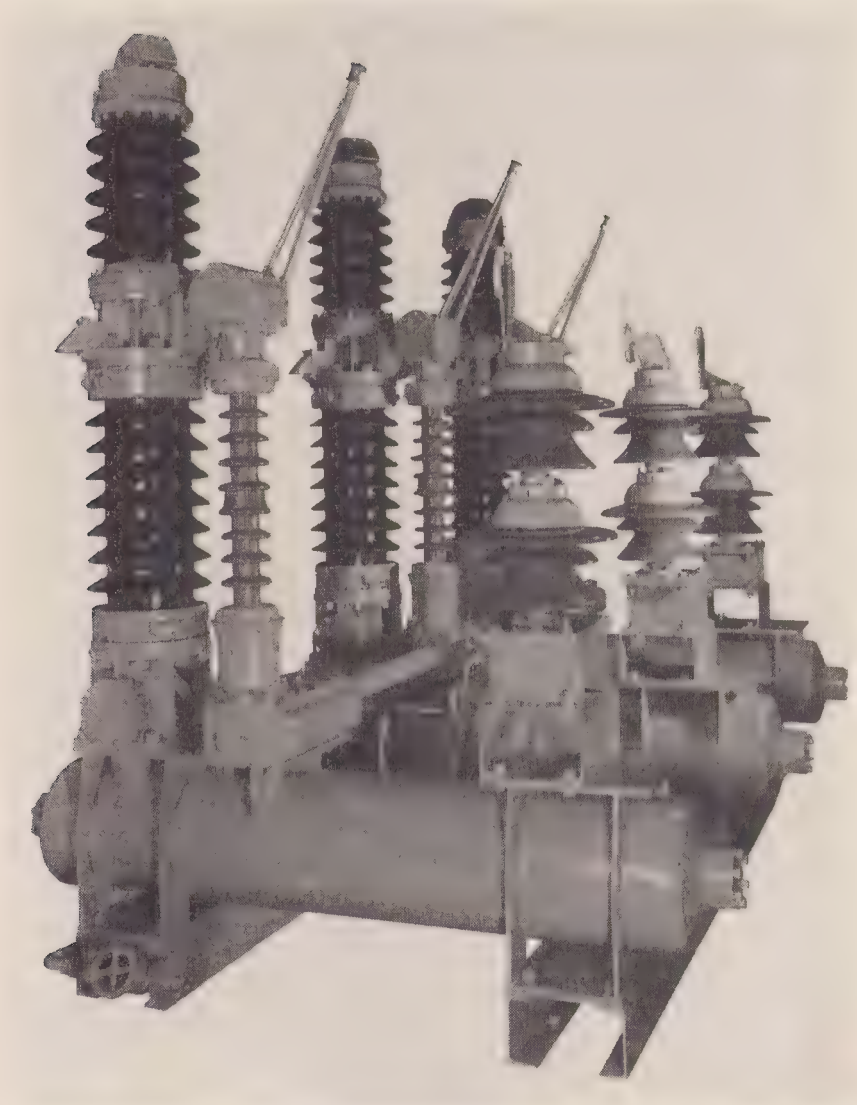


FIG. 10-20.—*66 kV Duo-Blast Circuit-Breaker (Messrs. Ferguson, Pailin, Ltd.).*

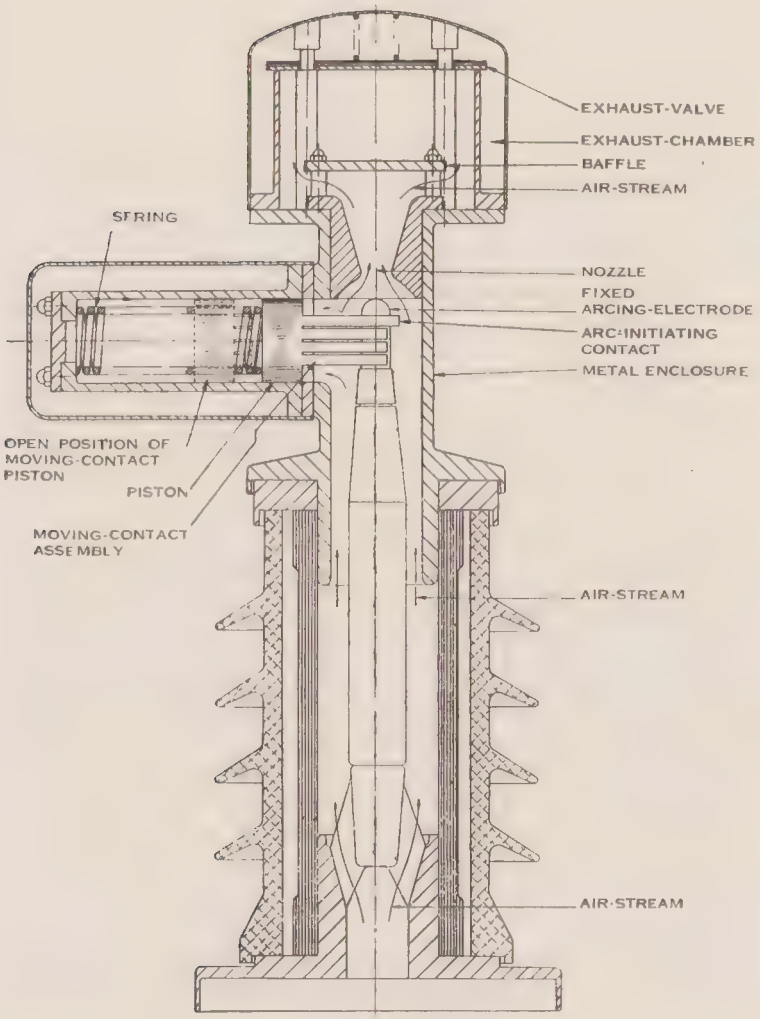


FIG. 1 CROSS-SECTION OF SINGLE AIR-BLAST TURBULATOR.

FIG. 10-21.—*Cross-section of Single Air-Blast Turbulator (A. Reyrolle & Co., Ltd.).*

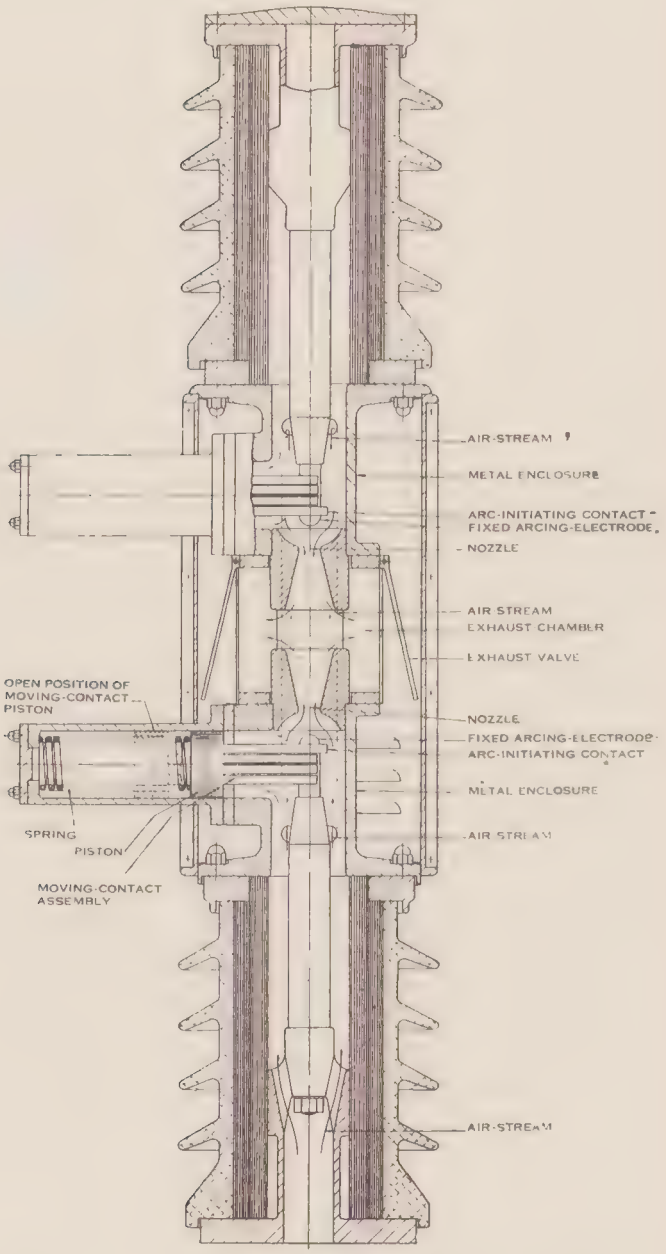


FIG. 10-22.—*Cross-section of Duplex Air-Blast Turbulator (A. Reyrolle & Co., Ltd.).*

Figs. 10-21 and 10-22 illustrate the single and duplex turbulators respectively. The moving contact assembly is mounted on a piston which moves laterally against a spring where the air pressure rises to a predetermined value. It acts as a bridging member between the fixed contact and the metal enclosure.

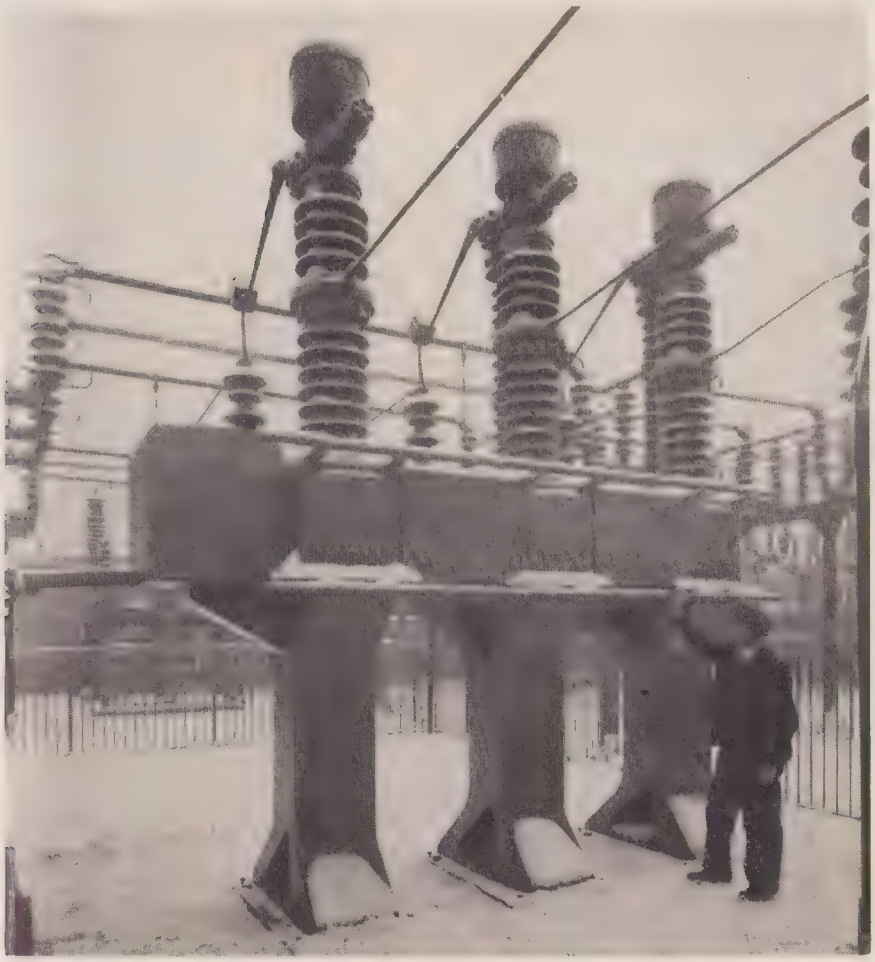


FIG. 10-24.—*66 kV Air-Blast Circuit-Breaker (A. Reyrolle & Co., Ltd.).*

To open the circuit, compressed air is admitted into the metal enclosure and the piston carrying the moving contacts is moved outwards, thereby transferring the current to the extended arc-initiating contacts, which on further movement initiates the arc in an air blast. The arc is then rapidly positioned through the nozzle between the fixed arcing electrodes situated in the high and low pressure zones. The duplex turbulator is a development

of the single turbulator. It has two sets of contacts as shown in Fig. 10-22, while in some constructions, there is an additional electrode between the two nozzles. This design of contacting arrangement has the advantage of the cross blast design in that it has main current carrying contacts which are unaffected by arcing in addition to arcing contacts.

In effect, the single air-blast turbulator is one half of the duplex turbulator and arc extinction takes place in it as described below, except that instead of two arcs merging into one common arc, there is only one arc with one arc root on the fixed arcing electrode similar to that of the duplex turbulator, and the other arc root on a fixed electrode on the other side of the nozzle.

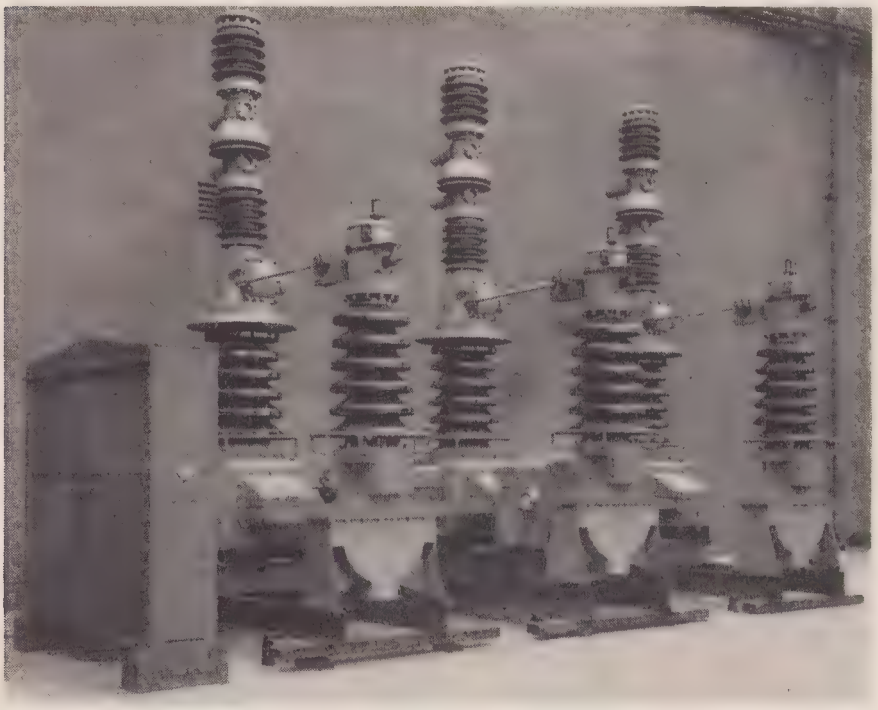


FIG. 10-25.—*110 kV Air-Blast Circuit-Breaker with local control cubicle (A. Reyrolle & Co., Ltd.).*

The stages of arc extinction in the duplex turbulator are shown in Fig. 10-23.

The normal closed position is shown at A. The contacts separate only when the air pressure reaches a predetermined value ensuring that the stream of air is established through the nozzles before contact separation. An arc is drawn laterally at the entrance to each nozzle into which a stream of compressed air is passing (see B) and is transferred rapidly from the moving arc-initiating contact to the nozzle (see C). The arc root is blown up the nozzle (see D) meeting the other arc which is similarly created, and the two arcs merge into one common arc (see E) centralised by the two air streams passing through the nozzles. The air-streams act on the arc to

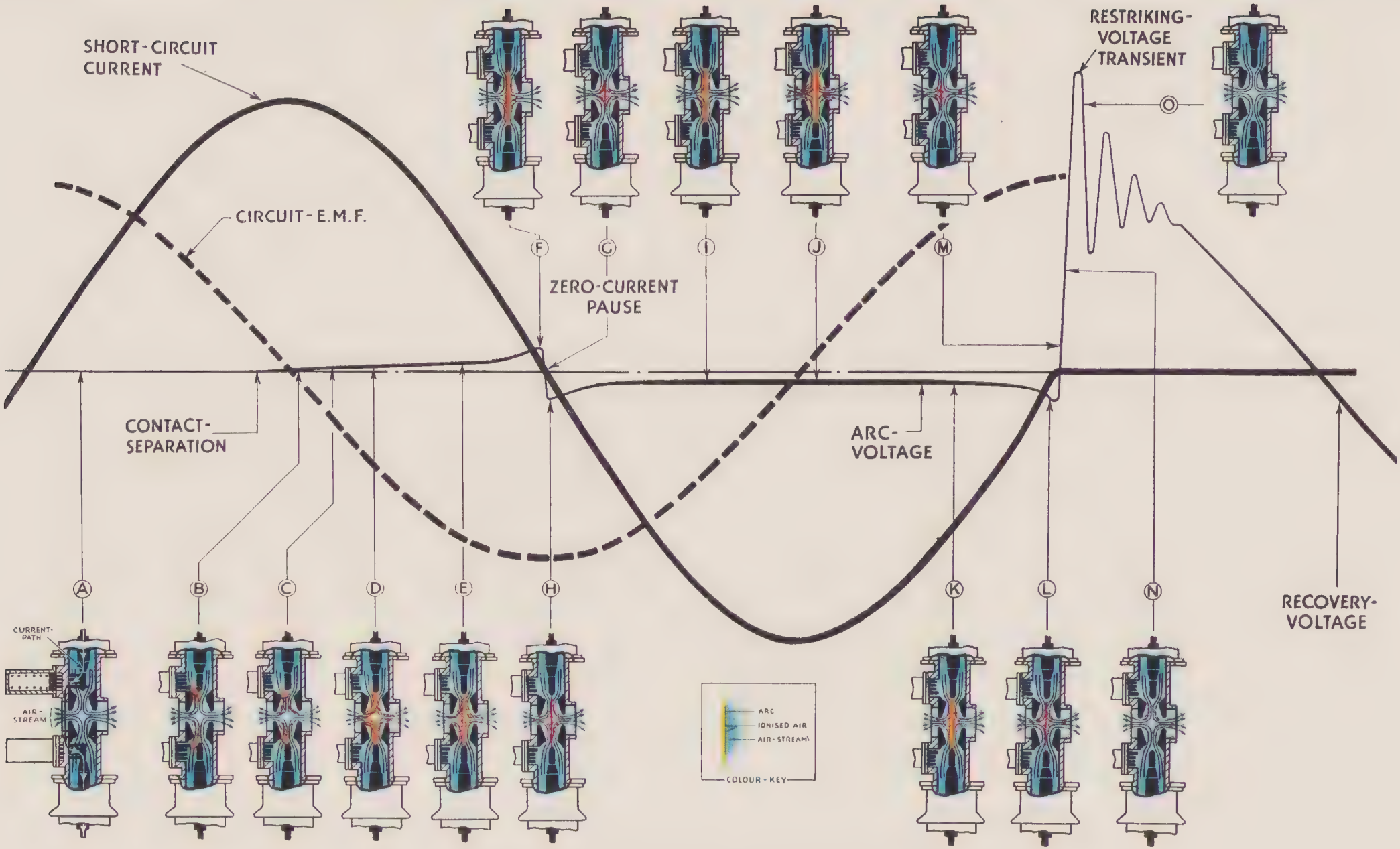


FIG. 10-23.—*Arc Extinction in the Duplex Air-Blast Turbulator*
(A. Reyrolle & Co., Ltd.).

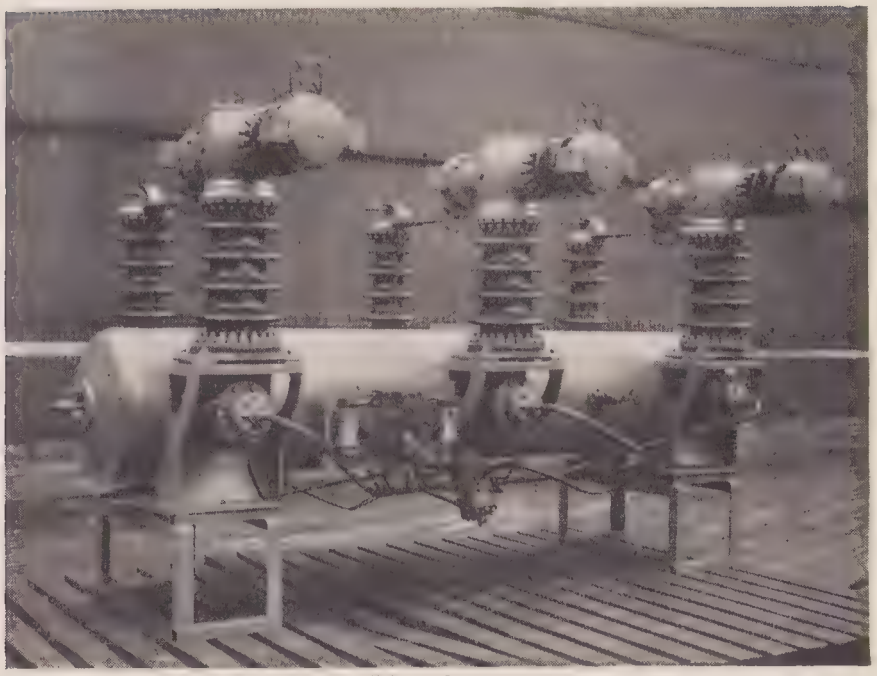


FIG. 10-26.—33 *kV Air-Blast Circuit-Breaker (Metropolitan-Vickers Electrical Co., Ltd.).*

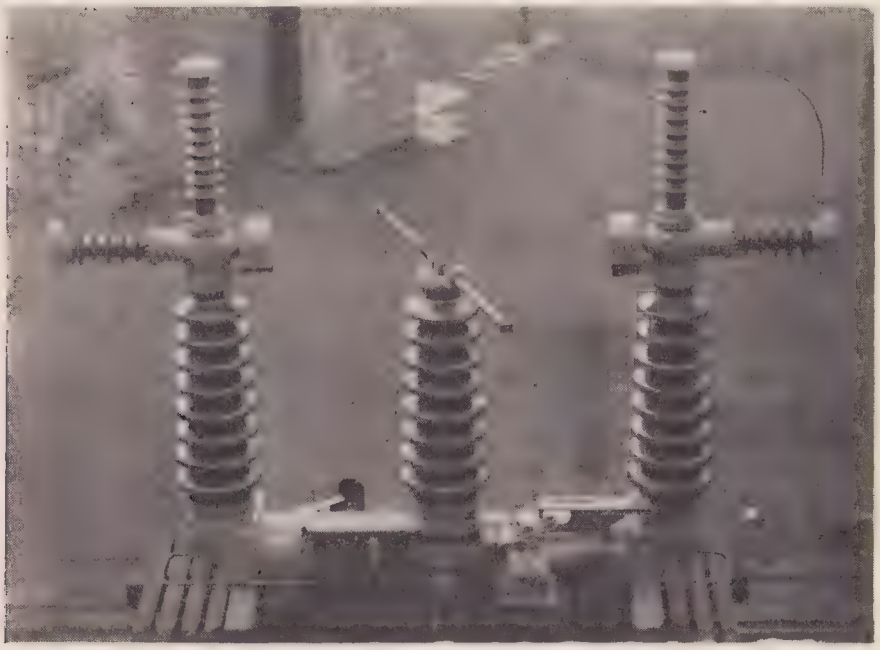


FIG. 10-27.—132 *kV Air-Blast Circuit-Breaker (Single Pole Unit) (Metropolitan-Vickers Electrical Co., Ltd.).*

counteract any tendency for it to be diverted from its centralised position, and at the same time sweep away any ionised gas from around the arc. This is important as while the current is falling the scavenging action of the air stream over the contracting surfaces of the arc reduces the ionisation round the arc to a minimum, so that when a current zero is reached (see G) there is only a thin thread of residual ionised gas to be de-ionised.

This happens most rapidly in the neighbourhood of the two nozzle throats and the process is helped by the rapid turbulence between hot and cool gases.

If the arc is not extinguished at the first current zero, the scavenging action of the air stream continues to cut down any residual ionisation (see H to K) and at the next current zero there is still only the small thread of ionised gas to be dealt with (see L), the de-ionising effect now available, which is determined by the air pressure, being greater than at the first current zero. The turbulence caused by the interaction between the hot residual gases and the cool gases of the rapidly moving air-stream breaks up the thread of ionised gas (see M and N) and so enables the residual arc-path to regain its electric strength and to withstand the restriking transient as indicated at O.

As in all axial blast designs where the retractable contact moves only a limited distance insufficient to provide normal isolation, a separate isolator is provided which operates only after the arc has been finally interrupted.

The Metropolitan-Vickers Electrical Co., Ltd., have introduced designs of air-blast circuit-breakers in recent years, of which the following is a brief description.

Each pole of the circuit-breaker has one or more arc-interrupting heads and a series switch-blade moving in free air. Fig. 10-26 is typical of the lower voltage construction and shows a 33 kV design. At higher voltages double-break sequence switches are employed, while at 110 kV upwards two double-axial blast-heads are fitted per phase, as shown in Fig. 10-27, which is a 132 kV type with each pole mounted on its own local air tank.

The interrupting heads are mounted horizontally and are shown in section in Fig. 10-28. Each head contains two hollow contacts one of which carries a piston which is driven backwards a limited distance when compressed air is admitted to the head enclosure.

The arc is struck between the annular contact rings but the roots of the arc are immediately driven inwards to the throats of the nozzles through which the compressed air exhausts to the outlet tubes. Here the roots lodge, the arc bridging the short gap between the nozzles, and, as the current approaches zero, bowing into the tubular exhaust passages as shown in Fig. 10-28 (b). This attenuated arc is extinguished at current zero, at which time completely fresh compressed air already occupies the shortest gap, Fig. 10-28 (c); that is, between the annular contact rings. This gap is large enough to withstand the restriking transient. Transfer of the arc-roots from the annular contact rings to the throats is so rapid that very little erosion takes place on the contact surface. The majority of the burning occurs in the throats and the small amount of metal volatilised therefrom is sprayed into the insides of the exhaust tubes. The air finally passes to atmosphere through coolers situated at the outer ends of the tube.

While the arc-breaking contacts are still held apart by the air blast, compressed air is admitted to a cylinder mounted on the base, the piston in which is linked to the post insulator carrying the series switch-blade, which is thereby rotated to the open position. This opening movement of

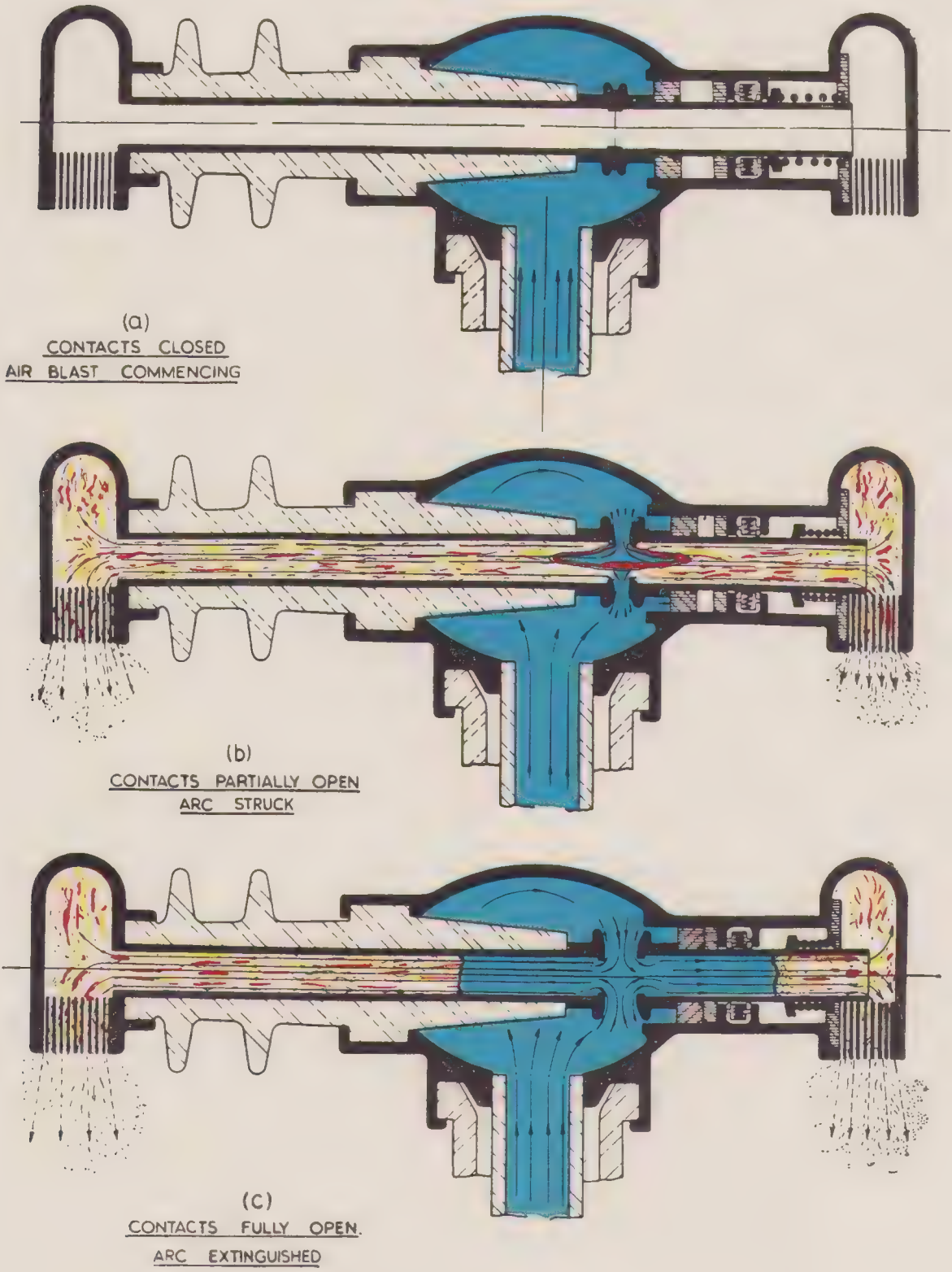


FIG. 10-28.

FIG. 10-28.—*Diagrammatic representation of the arc-breaking process on an Air-Blast Circuit-Breaker (Metropolitan-Vickers Electrical Co., Ltd.).*

the sequence-switch causes the blast valves to shut and the interrupting contacts to reclose under spring action. The object of the series switch-blade is to maintain interruption of the system after the air-operated nozzles have reclosed.

When the circuit-breaker is to be closed the post insulator is rotated in the reverse direction and the circuit is completed by the sequence-switch contacts in free air. It is, therefore, necessary that this movement be carried out very rapidly, in order to reduce the period during which arcing can persist between the approaching contacts should the circuit-breaker be closed on to a fault.

The form of fixed contact used to co-operate with the high-speed sequence-switch is such as to eliminate bounce on closing and to present the minimum resistance to opening, even under unfavourable conditions of icing.

The pneumatic operating mechanism includes essential interlocking to ensure that the circuit-breaker can only be left in the fully-closed or fully

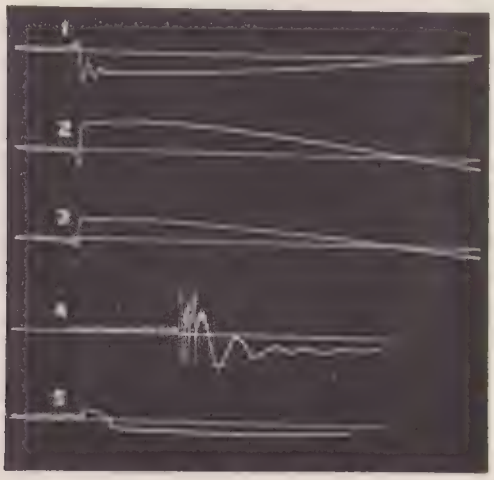


FIG. 10-29.—*Oscillogram showing the effect of using " Metrosil " shunting resistors (Metropolitan-Vickers Electrical Co., Ltd.).*

open positions, independent of the operator, and cannot hunt. The correct sequence of interrupting contact and series switch action is also ensured and operation below the minimum air pressure necessary for full rated short-circuit capacity is prevented.

The double-blast ensures ability to interrupt with the maximum rate of rise of restriking voltage of power distribution systems at the voltage for which the heads are designed. In addition the use of " Metrosil " as described later permits a high factor of safety for the interrupting ability of the arc gap, without risk of over-voltages when interrupting small, low power-factor currents.

The interrupting heads are fitted with shunt resistors of " Metrosil," which is a ceramic material having a non-linear voltage-current characteristic. These resistors serve to suppress any over-voltage that might otherwise

be produced by the powerful interrupting action of the nozzles when clearing light currents.

Fig. 10-29 shows oscillograms illustrating the effect. Curve 1 represents the natural restriking oscillation occurring when interrupting a short-circuit

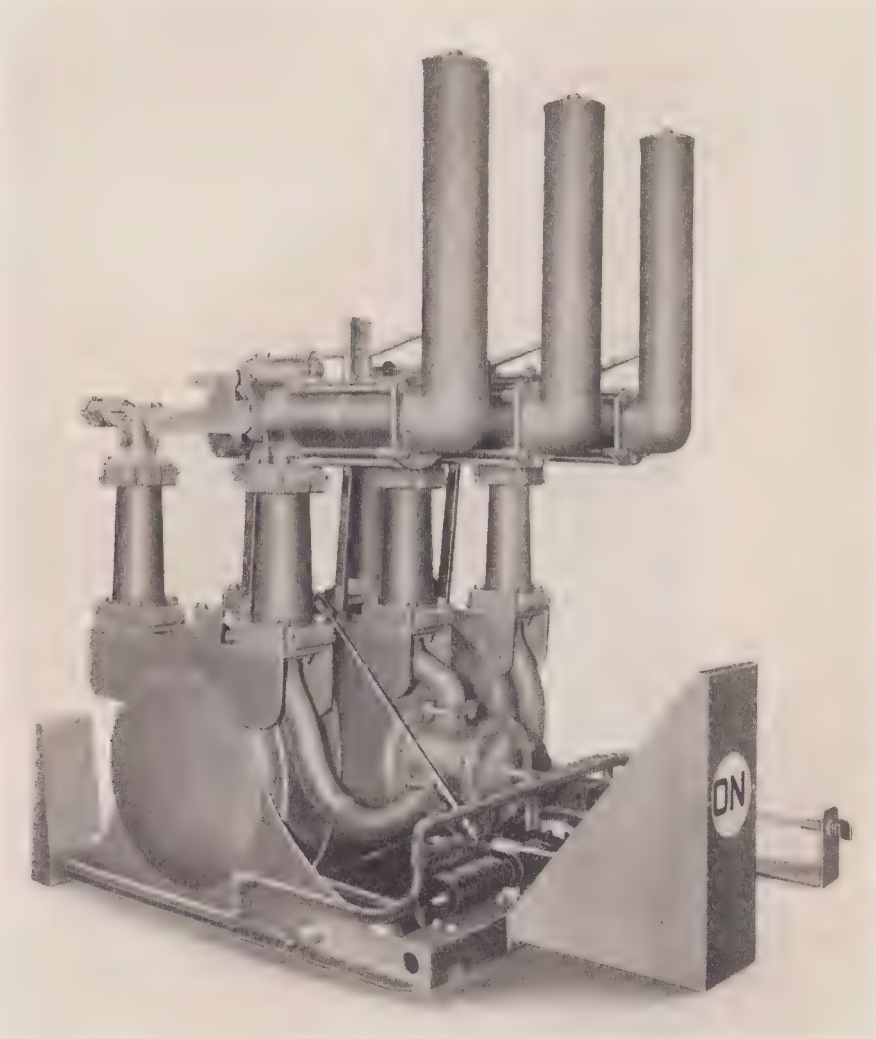


FIG. 10-30.—11 *kV Air-Blast Circuit Breaker (The English Electric Co., Ltd.).*

at heavy current. Curve 2 shows the damping effect of "Metrosil" on a similar test. Curve 3 shows the somewhat reduced damping effect obtained at a voltage of the order of two-thirds that for Curve 2. Curve 4 shows the violent oscillations occurring when interrupting small inductive currents

without " Metrosil," while Curve 5 shows the critical damping of such oscillations with the "Metrosil" inserted.

On account of the characteristics of this material, which suppresses the small resistance-current towards the current zero, the final interruption is easily effected by the sequence-blade in free air.

When used on circuit-breakers having two or more interruptors in series, the "Metrosil" resistors serve also to grade the restriking voltage transient uniformly between the different gaps. This is achieved because at all material voltages the resistance-current is sufficient to overcome the disturbing effect which would otherwise occur in restriking-voltage distribution due to the capacitances to earth of the various interrupting heads.

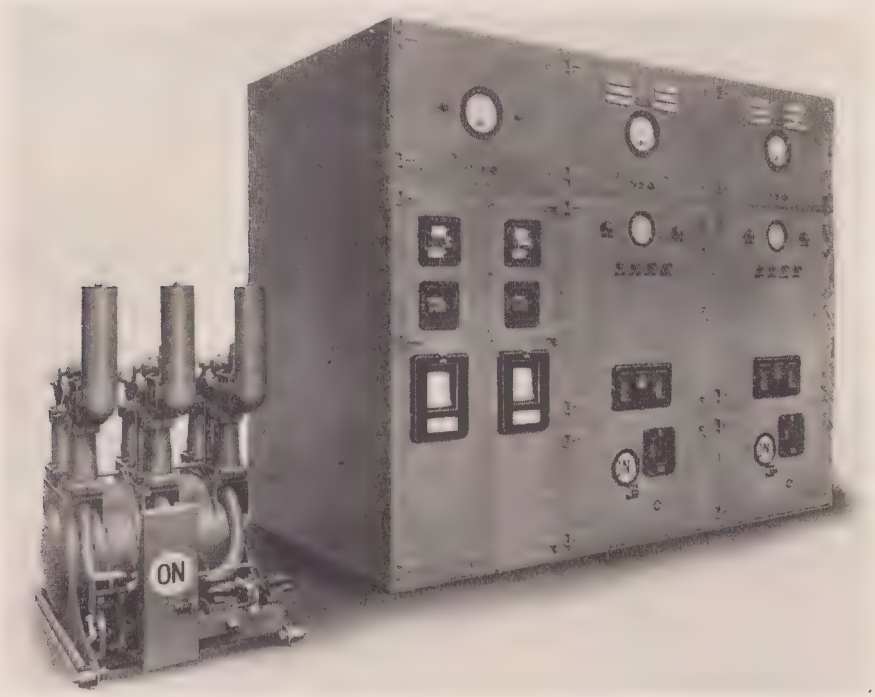


FIG. 10-31.—*Sheet Metal Switchboard with 11 kV Air-Blast Circuit-Breakers (The English Electric Co., Ltd.).*

It is therefore possible to ensure that with multi-head circuit-breakers each head will have to interrupt only its appropriate fraction of the total voltage associated with the short-circuit current. The arrangement therefore not only makes it possible to build circuit-breakers for the highest voltages at present envisaged, but it ensures the ability to do this at maximum rated-current and at extreme rates of rise of restriking-voltage.

All air blast circuit-breakers designed by The English Electric Co., Ltd., have interruptors with single flow axial-blast contacts, with an external make-switch which serves also as an isolator.

Up to and including 33 kV single gap interruptors with damping resistance are used and the resistances are operationally introduced by arc transfer.

At 66 kV either single or double plain gap interruptors are used depending upon the rating and style of breaker.

At 132 kV two series plain gap interruptors are used and at 264 kV four gaps are used.

The smaller breakers as in Figs. 10-30 and 31 have one main air valve which controls the extinguishing air to all three poles.

The larger breakers have a main valve at the base of each interruptor column. These valves can be operated independently to give single phase interruption with auto reclosing or together to give normal 3-phase circuit clearance.

There are two groups of breakers, the indoor units up to and including 66 kV and the outdoor units at 66 kV and 132 kV.

At voltages up to the order of 33 kV a high breaking capacity breaker has an interruptor gap which tends to produce an electric strength which is too great and may permit dangerous over voltages. Resistances are applied as shown in Fig. 10-32, an arrangement which entails little complication and uses a common air stream. The breakers in Figs. 10-30, 10-33 and 10-34 employ this principle.

At 66 kV and above, resistances are not necessary as it is possible to produce a contact system that will handle high short-circuit currents and at the same time control restriking voltages within safe limits. The single nozzle axial blast contact is used because it has the fundamental advantage of minimum gap length and, in consequence, maximum inherent over voltage protection.

The 11 kV 500 MVA, 3-phase unit shown in Fig. 10-30 is constructed as follows :—

An air receiver forms the body of the unit and upon this are mounted a main valve, two control valves, anti-hunting relay, auxiliary switches, and six support insulators, two per phase. Each pair of insulators carries main contacts within an arcing chamber and an isolator together with damping resistance and cooler. The support insulators are hollow and one of each pair forms an air conduit from the receiver via the common main valve to the arcing chamber.

At one end of each arcing chamber is a nozzle shaped fixed contact. This is associated with a moving contact in the form of a piston having a rod with a rounded end which lies up to the fixed contact under the action of a spring. When the breaker is opened an electrical impulse is given to the " Opening " control valve which operates to release the main valve and air under pressure from the receiver flows to the arcing chambers.

Pressure is built up in each arcing chamber and the moving contact is withdrawn and enveloped in a high velocity air stream which passes through the fixed nozzle contact into a cooler, sweeping the arc and its products away in its path. When the moving contacts reach the end of their stroke, air is admitted to the isolator operating cylinder and the isolators are opened. The main valve is then closed and all air cut off.

The sequence of operation is shown in Fig. 10-32.

On closing, the main valve does not come into operation. An electrical impulse is given to the anti-hunting relay and the closing control valve is energised and opens to admit air into the isolator closing cylinders. The isolators then close to make the circuit and the air is again automatically cut off.

The use of damping resistance permits a reduction of air consumption in that they serve to damp down the restriking voltage while the main gaps

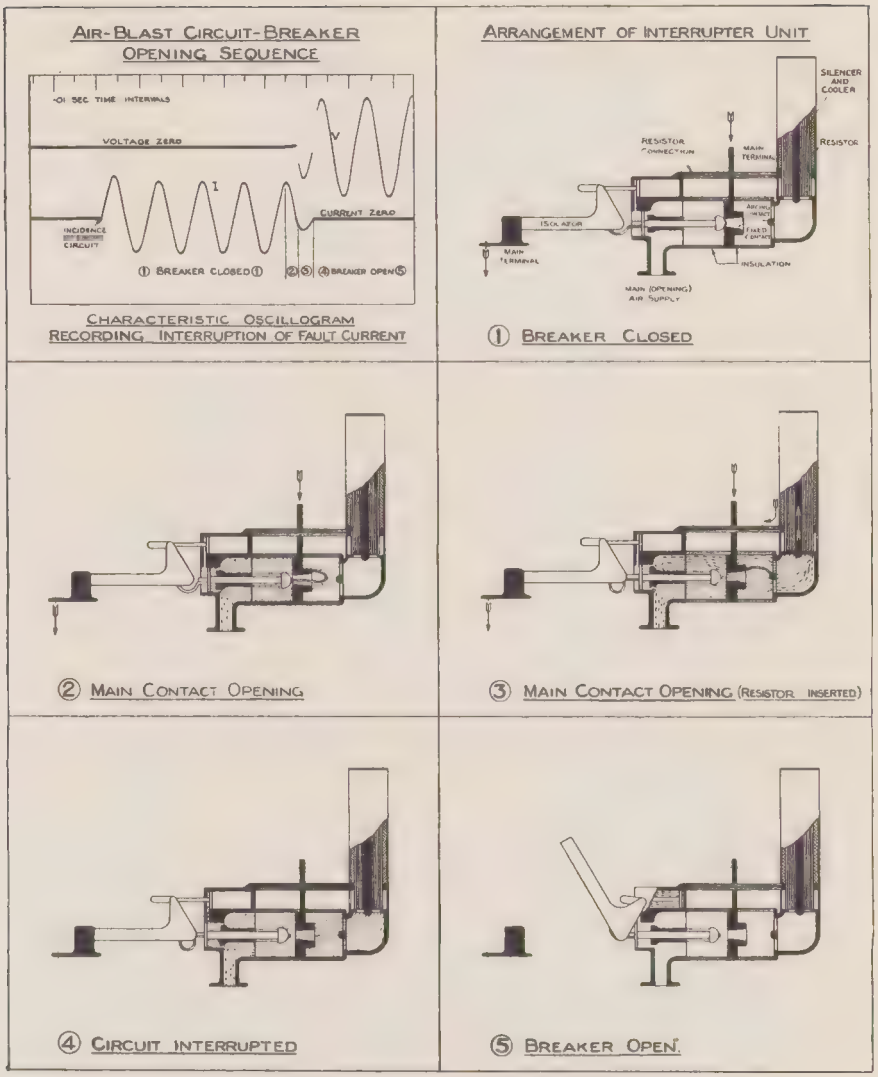


FIG. 10-32.—*Opening Sequence of Axial-Blast Circuit-Breaker (The English Electric Co., Ltd.).*

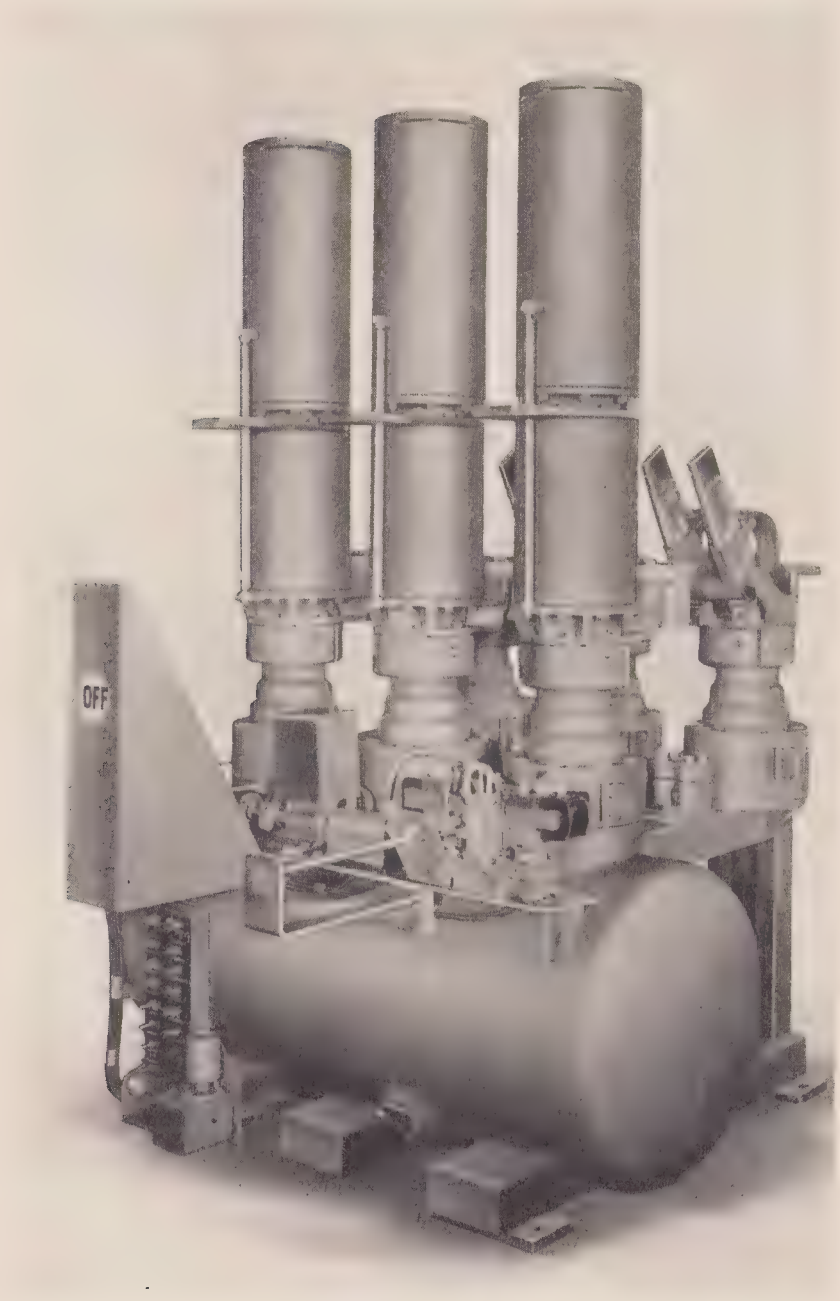


FIG. 10-33.—6·6 *kV* 1,600 *amp. Indoor Air-Blast Circuit-Breaker* (*The English Electric Co., Ltd.*).

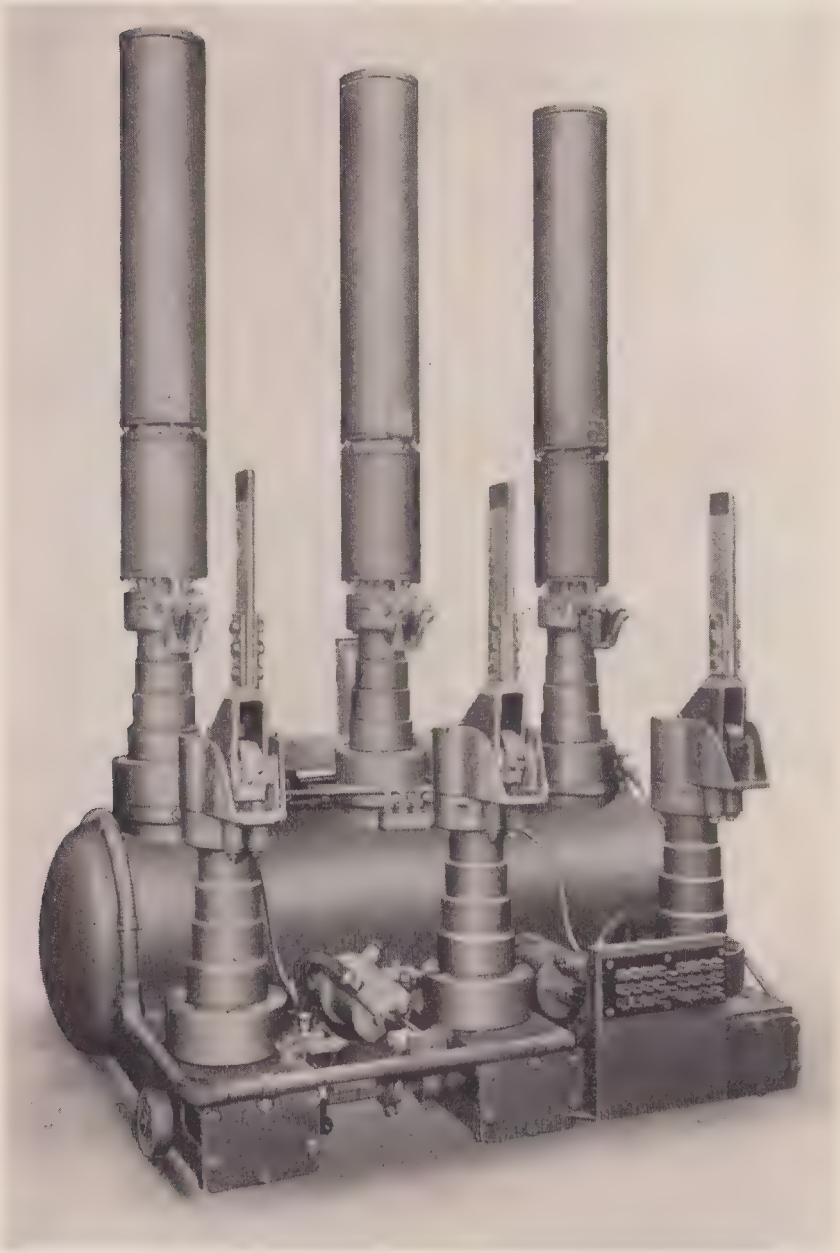


FIG. 10-34.—33 *kV* 1,600 *amp. Indoor Air-Blast Circuit-Breaker (The English Electric Co., Ltd.).*

are being cleared of ionised arc products. The application of resistances at 66 kV and above is claimed to be inconvenient and hazardous, A better way of conserving air is to adopt the restricted cooler as shown in Fig. 10-35, which illustrates a plain break 132 kV 2,500 MVA interruptor column having two single flow axial blast gaps per phase. Pressure air flows up the support insulator A to envelope and depress contacts B (as

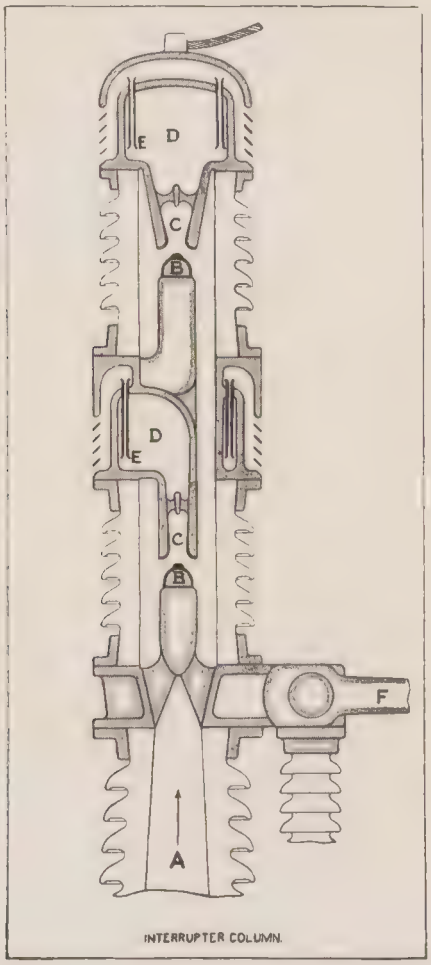


FIG. 10-35.—*Sectional View of Interruptor Column 132 kV (The English Electric Co., Ltd.).*

shown) thus drawing twin arcs. The arcs and their products are swept through nozzles C into the restricted coolers D where they are cooled and from whence they escape comparatively slowly through restrictor tubes E to atmosphere.

The coolers are proportioned so as to accept full air flow through the nozzles C for approximately 0.04 seconds, after which an accumulating

back pressure reduces the flow in the gap to a mere drift of clean air at full pressure. The gaps are held open and the electric strength is maintained for a very small expenditure of air until the isolator F is fully open. Overall air consumption does not exceed that of an equivalent resistance breaker.

This principal is used on the breakers shown in Figs. 10-36, 10-37 and 10-38.

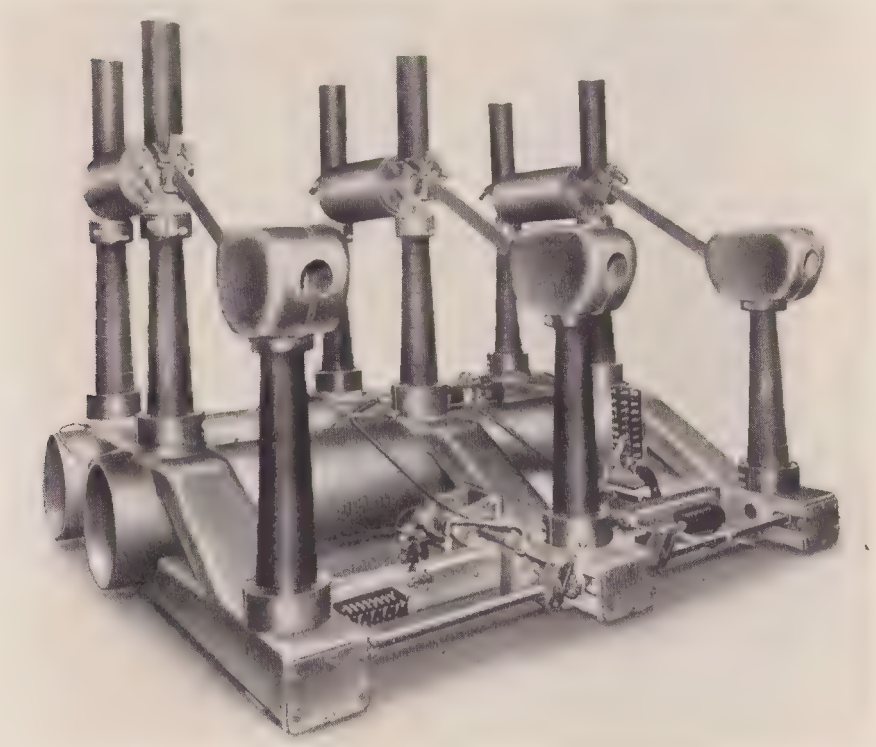


FIG. 10-36.—*66 kV 800 amp. Indoor Air-Blast Circuit-Breaker (The English Electric Co., Ltd.).*

The 66 kV indoor breaker has two breaks which are arranged so that voltage distribution is controlled by the electrostatic capacity of the contact system. Tests have proved a voltage division of the order of 60% and 40%. The 132 kV outdoor breaker (Fig. 10-38) cannot easily be arranged for inherent capacity control, and in this case voltage distribution is obtained by the use of conducting glaze over the interruptor insulators.

In designs using the separate isolator, this has to be suitable for the final " making " of the circuit, because the retractable main moving contact is already in the closed position. This means that the isolator must be robust in design, able to close right home without bounce on a " making " test. It is designed to perform this duty in air at atmospheric pressure. It is

important that the series isolator must open only after final arc extinction within the arcing chamber. This is achieved by suitable time delays on the operating mechanism, the latter being carefully timed in relation to the main opening functions.

It is of interest to consider the limited movement of the retractable contact in axial blast designs. It can be shown that the interrupting capacity is affected by and depends on the nozzle diameter, the air pressure and

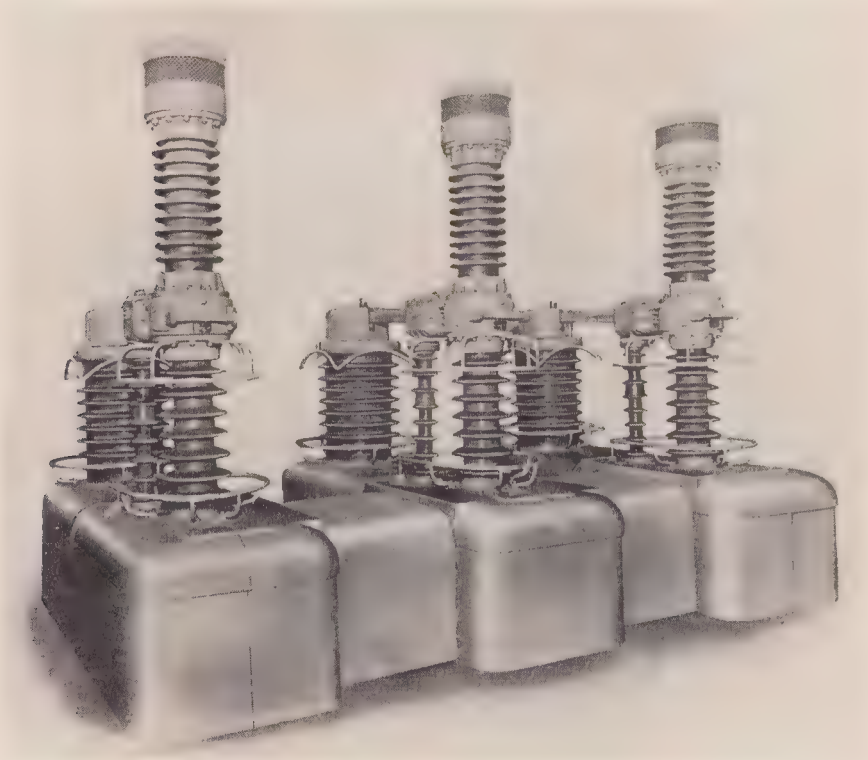


FIG. 10-37, 66 *kV* 800 *amp. Outdoor Air-Blast Circuit-Breaker (The English Electric Co., Ltd.).*

the travel of the contacts, *i.e.*, the gap. Interrupting capacity does not rise uniformly with increasing contact travel. Instead it reaches a maximum value and then diminishes rapidly as the gap becomes greater. This feature is illustrated in Fig. 10-39* A relatively small gap has been shown to be most favourable but as this does not provide sufficient dielectric strength between the fixed and moving contacts after the air stream has ceased, it is necessary to provide series isolators.

In some designs, the latter have been dispensed with and by delaying the travel of the moving contact at a point in its total travel, arc extinction is assured without long arcing times, after which the moving contact travels on to give ample isolation.

**With aknowledgments to Brown-Boveri and Co., Ltd., and to an article in "Brown-Boveri Review," November/December, 1942, by H. Thommen.*

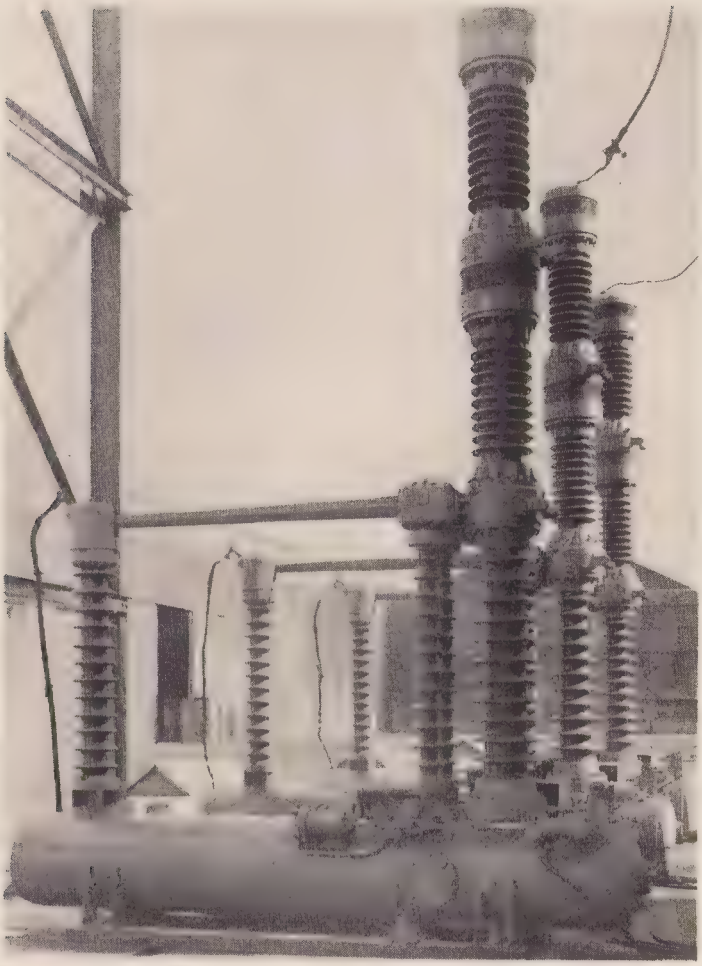


FIG. 10-38.—*132 kV Outdoor Air-Blast Circuit-Breaker (The English Electric Co., Ltd.).*

Fig. 10-40* will serve to illustrate the three possible conditions :—

(*a*) Continuous movement of the moving contact to provide ample isolation.

(*b*) Delayed movement at the most favourable position for arc extinction.

(*c*) Limited movement, involving separate series isolation.

The travel of the contacts is a critical factor in determining breaking capacity. If the gap is too small the breakdown voltage will be reduced and restriking after current zero will take place. The narrow gap will also

**With acknowledgments to Brown-Boveri and Co., Ltd., and to an article in the "Brown-Boveri Review," November/December, 1942, by H. Thommen.*

restrict the flow of air, and the velocity of the gas at the arc root will be decreased. On the other hand, if the gap is too large the arc becomes too long and is not so easily controlled and guided by the air stream.

The flow of air past the edge of the orifice should be as turbulent as possible to cause intermingling of the ionized gas and the cool air so that the maximum cooling and deionization of the arc takes place after current zero. The maximum velocity is obtained when the pressure on the exhaust side of the orifice is less than one-half of that on the incoming side, under

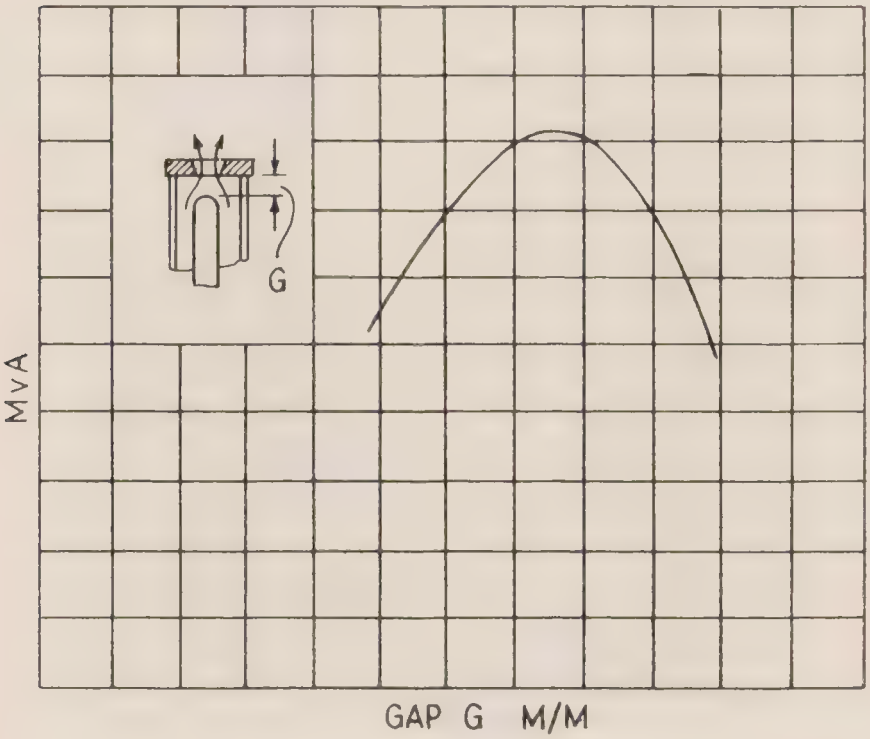
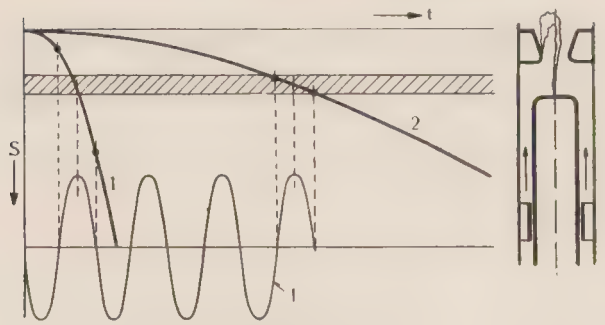


FIG. 10-39.
(*Brown-Boveri & Co., Ltd.*).

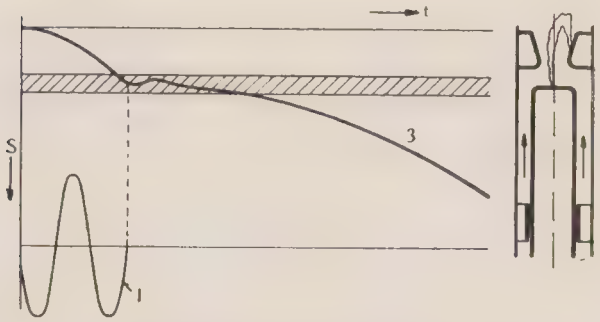
which condition the air stream has the velocity of sound. Increase in air pressure leads to an increase in rupturing capacity by increasing the density of the air adjacent to the arc, so greatly assisting recombination at current zero. Similarly, an increase in the diameter of the orifice in the contacts gives an increase in the quantity of air passing through them, clearing the ionized gas away more rapidly, and thus accelerating the re-establishment of the electric strength across the contacts and increasing the breaking capacity.

COMPRESSED AIR INSTALLATIONS.

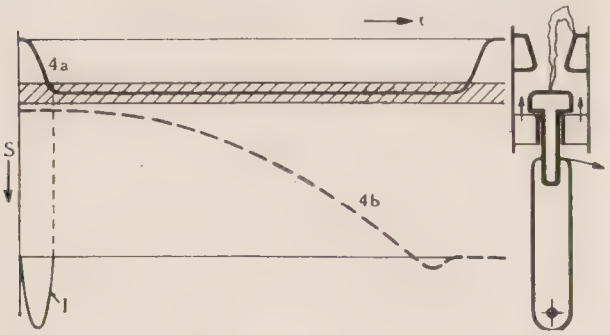
The compressors for providing an adequate supply of air are usually of the two stage type. Air is compressed to a pressure higher than that



(*a*) 1 = *High speed of opening.*
2 = *Slow speed of opening.*
I = *Current.*



(*b*) 3 = *Delayed opening stroke at favourable position for arc extinction.*
I = *Current.*



(*c*) 4*a* = *Limited movement.*
I = *Current.*

FIG. 10-40.
(*Brown-Boveri & Co., Ltd.*).

required at the circuit-breaker, thus assisting the supply of dry air. Local receivers at each circuit-breaker are fed from the compressor through a suitable reducing valve.

The installation differs from the more normal types associated with continuous process work in that air is taken in large amounts at infrequent intervals. It is, therefore, important that air leakage in pipe work, etc., be kept within reasonable bounds as this dictates the size of containers and equipment.

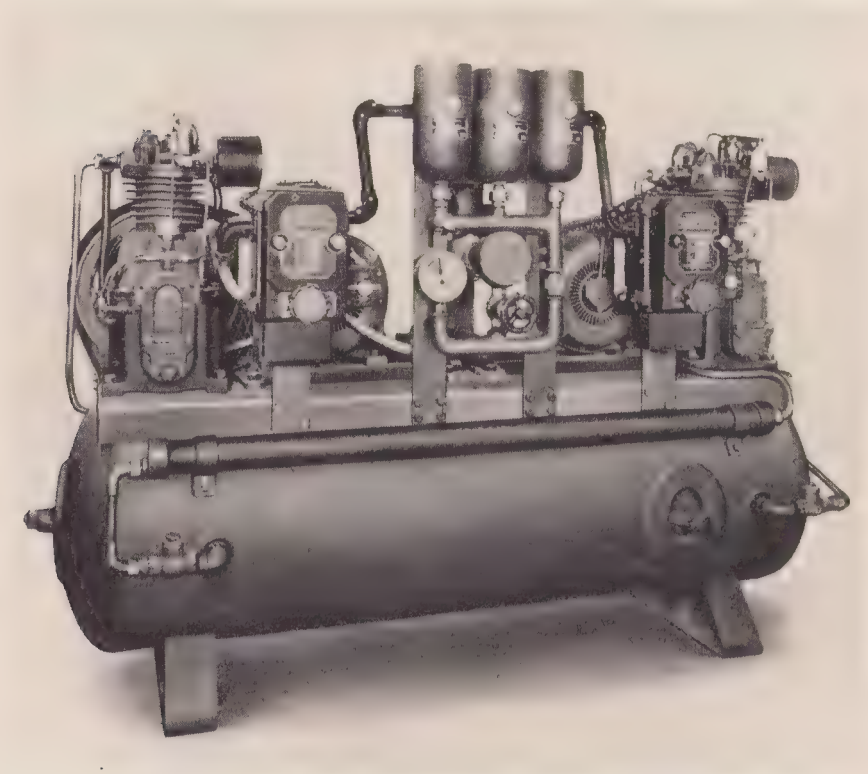


FIG. 10-41.—*Typical Self-contained Air Compressor Equipment with 2-stage Compressors (English Electric Co., Ltd.).*

It is most important that the air supply to the circuit-breaker should contain a minimum quantity of moisture. There are several reasons for this, the most important being the danger of freezing at valves, and the danger of condensation on insulator surfaces. The latter tends to reduce the electrical resistance and increases the liability to flash-over. In some designs, it is usual to allow a trickle of dry air to pass continuously over the insulating surfaces to maintain them in good condition. Apart from the storage at pressures in excess of the working pressure, other methods adopted to ensure dryness are the use of drying agents (*e.g.*, silica gel), water separators, and refrigeration. The importance of dry air increases as the system voltage increases, and is more important for outdoor installations than for indoor.

The high pressure air equipment must be designed to satisfy the relevant British Standard Specification and must comply with the requirements of the Factory Acts. It is important that provision be made for the regular inspection demanded by the Factory Acts, which require every air receiver to be thoroughly cleaned and examined at least once every 26 weeks.

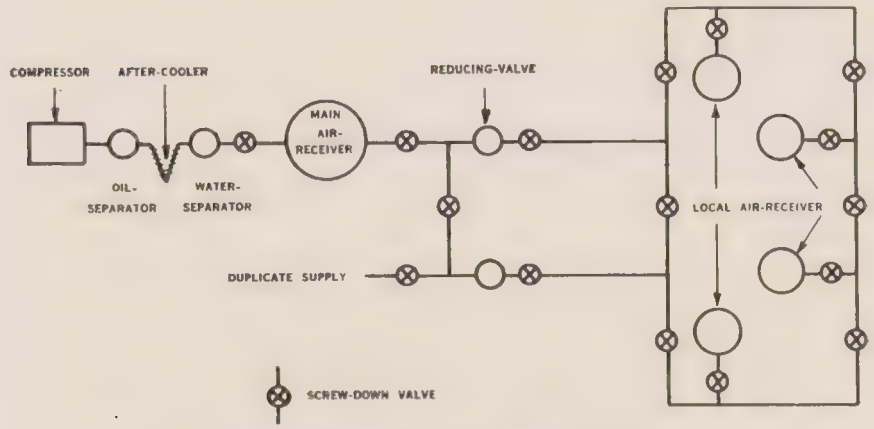


FIG. 10-42.—*Compressed-air Equipment for four Air-Blast Circuit-Breakers (A. Reyrolle & Co., Ltd.).*

The compressor will be a self contained unit with driving motor and control gear. It will be automatic in operation and will supply make-up air to the local receiver in a matter of seconds. Fig. 10-41 shows a typical installation.

Unless automatic reclosure of the circuit-breaker is required, the capacity of the local receiver is usually sufficient for one make-break duty cycle.

The arrangement of air pipes demands consideration from the point of view of ensuring reliability of supply under all conditions. In some installations a ring main air pipe is provided as shown in Fig. 10-42. In others, a duplicate bus pipe system is provided.

In all installations it is essential to ensure :—

(1) That air pressure in the local receiver is restored in a matter of seconds,

(2) That low-pressure cut-outs are provided to ensure that circuit-breaker operation is prevented when the pressure in the local receiver is too low,

(3) That suitable devices give warning of over pressures or excessive leakage,

(4) That the central air storage in the compressor house is normally such as to provide at least an additional make-break operation for each circuit-breaker in the installation.

BIBLIOGRAPHY.

" Air-Blast Circuit-Breakers," A. R. Blandford, " Journal I.E.E.," Vol. 90, Part II, No. 18, December, 1943.

" Restriking Voltage as a Factor in the Performance, Rating and Selection of Circuit-Breakers," J. A. Harle and R. W. Wild " Journal I.E.E., " Vol. 91, Part II, No. 24, December, 1944.

" The Influence of Resistance Switching on the Design of High-Voltage Air-Blast Circuit-Breakers," H. E. Cox and T. W. Wilcox, " Journal I.E.E.," Vol. 91, Part II, No. 24, December, 1944.

" Restriking Voltages," J. R. Mortlake, " BTH Activities," Vol. 18, No. 7, July, 1944.

" The Extinction of the Arc in Single and Multiple-Break Air Blast High Speed Circuit-Breakers," H. Thommen, " Brown Boveri Review," November/December, 1942.

" High-Voltage Outdoor Air Blast Circuit-Breakers," W. A. McNeill, " Engineering," August 24, 1945.

" A New 15 kV Pneumatic Circuit Interrupter," L. R. Ludwig, H. L. Rawlins and B. P. Baker, " Electrical Engineering," " Journal A.I.E.E.," Vol. 59, September, 1940.

" Design and Construction of High-Capacity Air-Blast Circuit-Breakers," H. E. Strang and A. C. Boisseau, " Electrical Engineering," " Journal A.I.E.E.," Vol. 59, September, 1940.

" The Cross-Air-Blast Circuit-Breaker," D. C. Prince, J. A. Henley, and W. K. Rankin, " Electrical Engineering," " Journal A.I.E.E.," Vol. 59, September, 1940.

" Circuit Interruption by Air Blast," W. S. Edsall and S. R. Stubbs, " Electrical Engineering," " Journal A.I.E.E.," Vol. 59, September, 1940.

" Air Blast Circuit-Breakers," W. A. Coates and C. H. Flurscheim, " The Metropolitan-Vickers Gazette," July, 1945.

" Air-Blast Circuit-Breakers," T. W. Wilcox, " Electrical Times," July 8, 1943.

" The Evaluation of Restriking Voltages," J. R. Mortlake, " Journal I.E.E.," Vol. 92, Part II, No. 30, December, 1945.

" Factors influencing the Design of High-Voltage Air-Blast Circuit Breakers," C. H. Flurscheim, B.A., and E. L. L. Estrange, M.Eng., " Journal I.E.E.," Vol. 96, Part II, No. 52, August, 1949.

CHAPTER XI

LOW-VOLTAGE H.R.C. FUSES AND THEIR APPLICATION

LOW-VOLTAGE fuses may be segregated roughly into two classes: those of the semi-enclosed type with a strand or strands of wire stretched between terminal blocks and carried in a moulded or porcelain handle (Fig. 11-1), and those of the cartridge type, where the fusible elements are within a ceramic body which is completely powder-filled (Fig. 11-2).

The first type has a limited use, in particular on systems where only medium or low values of fault current can occur. They suffer a considerable disadvantage in that they are open to alteration at the will of the user without regard to safety or the characteristics of performance demanded.

FIG. 11-1.—*Typical Porcelain Handle Fuse of the re-wireable type.*

The second type, on the other hand, can be, and is, designed for use on systems of high fault value, cases being on record where they have successfully cleared faults up to 40 MVA at 440 volts, a.c. They are incapable of modification by the user and are capable of precision production to give consistent performance which can be predicted by the designer within very close limits.

In the past few years, considerable study has been made of the cartridge fuse and much research has been undertaken. Some indication of this

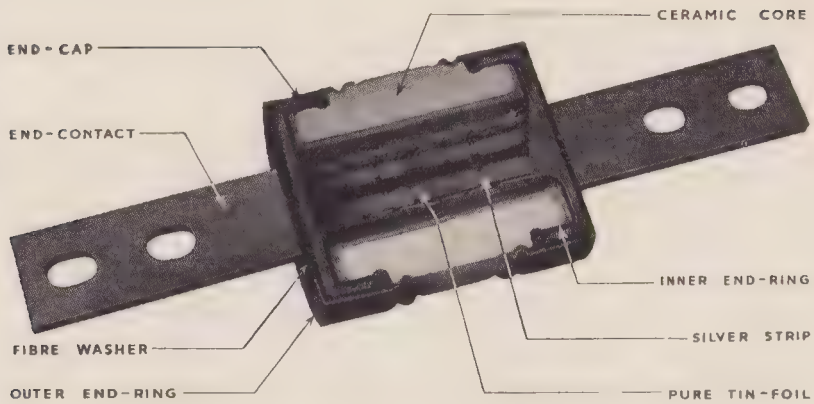


FIG. 11-2.—*Sectional view of typical Class GP Type 5 Cartridge Fuse-Link (Messrs. A. Reyrolle & Co., Ltd.).*

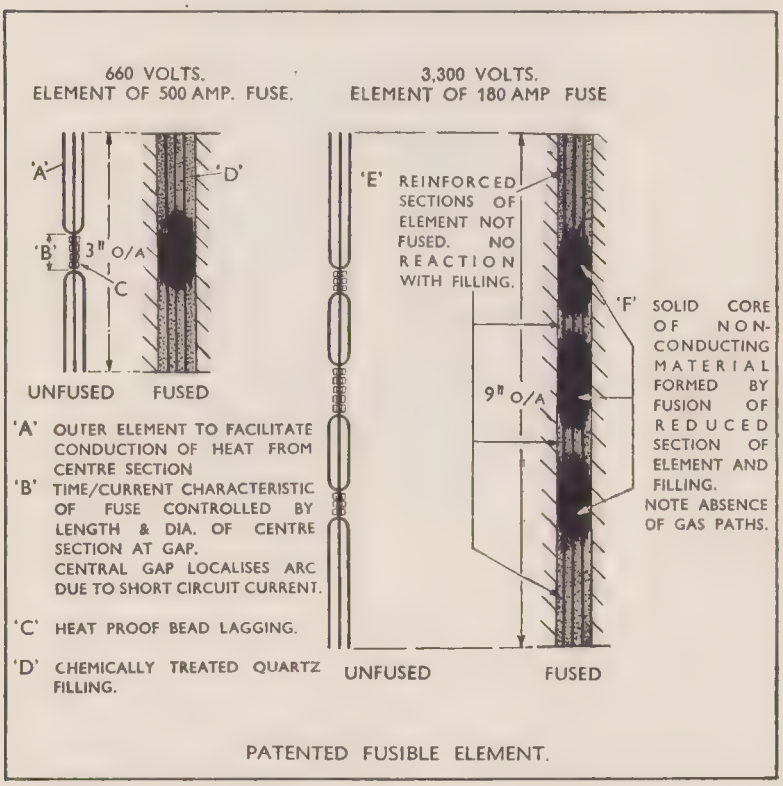

660 VOLTS.
ELEMENT OF 500 AMP. FUSE.
3,300 VOLTS.
ELEMENT OF 180 AMP FUSE
'A'
'D'
'B'
3" O/A
C
'E' REINFORCED SECTIONS OF ELEMENT NOT FUSED. NO REACTION WITH FILLING.
'F' SOLID CORE OF NON-CONDUCTING MATERIAL FORMED BY FUSION OF REDUCED SECTION OF ELEMENT AND FILLING. NOTE ABSENCE OF GAS PATHS.
9" O/A
UNFUSED
FUSED
'A' OUTER ELEMENT TO FACILITATE CONDUCTION OF HEAT FROM CENTRE SECTION
'B' TIME/CURRENT CHARACTERISTIC OF FUSE CONTROLLED BY LENGTH & DIA. OF CENTRE SECTION AT GAP. CENTRAL GAP LOCALISES ARC DUE TO SHORT CIRCUIT CURRENT.
'C' HEAT PROOF BEAD LAGGING.
'D' CHEMICALLY TREATED QUARTZ FILLING.
UNFUSED
FUSED
PATENTED FUSIBLE ELEMENT.

FIG. 11-3.—*Fusible Element of "English Electric" High Rupturing Capacity Fuse.*

work is given in various papers named in the bibliography, a recent contribution being that by J. W. Gibson. In addition, the knowledge gained has led to the need for a complete revision of B.S.88 and in this users of what have become known as h.r.c. fuses, will find a wealth of information based on recent study and research.

The relatively restricted use of the semi-enclosed fuse in switchgear applications which it is the intention of this work to cover, is such as to warrant the present chapter being devoted to the cartridge or h.r.c. fuse solely. In addition, as we shall see later, the advantages of the h.r.c. fuse, and in particular, that type which incorporates a tripping device, have led to other developments which provide protection against earth faults, a new method of time-limit fusing of overload coils, and for open-circuit protection for motor circuits.

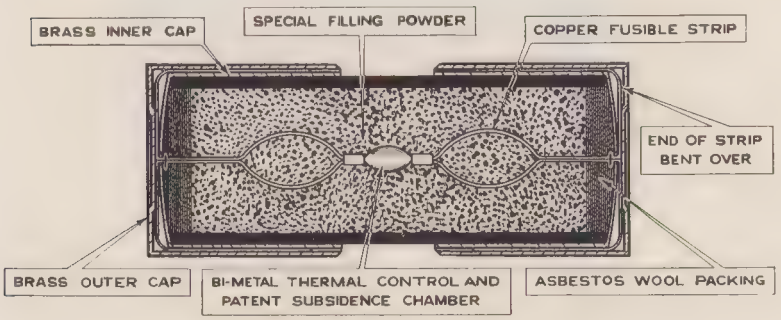


FIG. 11-4.—*" Aeroflex " High Rupturing Capacity Re-wireable Fuse, cross section of cartridge (Parmiter Hope & Sugden, Ltd.).*

Among the advantages of the h.r.c. fuse the following are important :—

(*a*) High short-circuit performance.
(*b*) Non-deteriorating.
(*c*) High speed of operation.
(*d*) Consistent performance.
(*e*) Reliable discrimination.
(*f*) Marked " cut-off " effect.
(*g*) Inverse time/current characteristics.
(*h*) Low cost compared with other forms of circuit interruptor of equal capacity.

Of these, (*a*) and (*f*) are of considerable importance in the applications to be described later.

In general, all types of h.r.c. fuses are similar. The body is a ceramic, specially heat resisting with a low co-efficient of thermal expansion, and of high strength to resist internal pressure. The main current carrying elements of silver are carried within this body and are connected by welding to metal end caps. Fig. 11-3 illustrates typical elements. The complete space within the body is solidly packed with a filling powder specially selected for its arc extinguishing properties.

In passing, it is of interest to note a variation of this type, where a composite metal fuse element is used, as indicated in Figs. 11-4 and 11-5.

Silver is chosen by designers because of its freedom from oxidation, its lower ohmic loss than copper, and the improvement it offers in cut-off effect.

As previously indicated, recent papers have dealt fully with the design and characteristics of the h.r.c. fuse, but it will be of interest here to relate briefly an outline of fuse operation. This comprises :—

(*a*) The melting of the silver elements.
(*b*) Element vaporisation.
(*c*) Fusion of silver vapour and the filling powder leading to powder "roping."
(*d*) Extinction of the arc by the fusion under (*c*).

FIG. 11-5.—*Element Construction of "Aeroflex" Re-wireable Fuse. The element consists of a copper strip having two narrow necks, between which the strip is interrupted by the insertion of a pocket of low melting temperature alloy. In clearing short circuits, the narrow necks operate as short-break quick acting fuses. In clearing overloads of lesser degree, the alloy pocket melts out and opens the circuit (Parmiter Hope & Sugden, Ltd.).*

The electrical phenomena associated with the foregoing are :—

(*a*) The creation of a high resistance by the chemical reaction to silver vapour and filling powder.
(*b*) The transmutation of the high resistance into an insulator by the simultaneous decrease of the fault current and the high temperature generated within the fuse by the fault current at the instant of interruption.
(*c*) The creation of a transient voltage within the fuse at the instant of breaking fault current due to the sudden change of energy.

The physical phenomena associated with fuse operation include a sudden rise of temperature and the creation of intense internal pressure derived from the release of energy consequent on the interruption of fault current.

To achieve the excellent performance which is a feature of the h.r.c. fuse, it is essential to obtain effective control of both electrical and physical phenomena. This control involves :—

(1) The arc must be extinguished in a minimum of time, and the shorter this is the higher the breaking capacity, provided always that the transient voltage is effectively controlled. Arcing within the fuse body creates high temperature which rapidly diminishes with rapid arc extinction, and the rate of temperature decline must be such as to reduce the hazard of pressure tending to shatter the ceramic body. Both rapid arc extinction and the

attainment of a satisfactory decline in temperatures are major functions of the filling powder. This must possess the necessary chemical attributes to coalesce perfectly with the vaporised silver, and must be ample in volume to surround each fusible element so that there is an adequate margin of safety for the work involved. It is essential, too, that the configuration of the fusible element be antipathetic to sustained arcing. The long thin element, uniform throughout as shown in Fig. 11-6, leads to much quicker arc extinction and temperature control than one which constitutes a short bridge between two relatively large metal end extensions as shown in Fig. 11-7.

Under arcing conditions, the voltage drop per unit fusible length for a short element is much higher than for a long element.

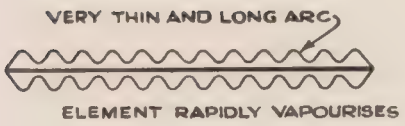


FIG. 11-6.
(*Electric Transmission, Ltd.*).

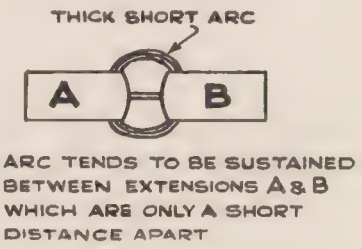


FIG. 11-7.
(*Electric Transmission, Ltd.*).

(2) The transient voltage created by the sudden interruption of fault current must be limited to a value low enough to eliminate any possibility of internal flashover, or a flashover of the insulation of adjacent apparatus. Control of this voltage is achieved by utilising fusible element sections which are such as to enable complete dissipation of the elements to be effected during the interrupting process, and to enable the arc resistance plus the current time differential to be effectively controlled during the period of current decrease.

The h.r.c. fuse as an interrupting device is, without doubt, *par excellence*. Its high performance in short-circuit clearance is largely due to current restriction, an effect to which the designation " cut-off " has been given.

This term expresses clearly what happens, and in simple terms it means that whereas in a short-circuited system without fuses the peak current in the first major loop of short-circuit may reach the value shown at (*a*) in Fig. 11-8, a fuse or fuses in the same circuit will function to interrupt the circuit when the current reaches a much smaller value, as at (*b*). The operation of a fuse depends largely on the melting of the elements at a certain temperature, which is reached rapidly, such melting occurring at current values much lower than the maximum. The deciding factor is the energy required to melt the fuse element. It must be noted, however, that a fuse does not exhibit cut-off at all values of prospective current but

only when the latter exceeds a particular value. The curves in Fig. 11-9* illustrate the cut-off effect in one design of cartridge fuse. From these curves it will be seen that whereas an 800 ampere fuse on a prospective fault of 30,000 ampere r.m.s. will cut-off at 21,500 amperes, this same fuse does not exhibit cut-off if the prospective fault current is less than about 4,000/5,000 amperes r.m.s. noting that in an asymmetrical fault this represents 7,200/9,000 amperes *peak*.

In determining the breaking capacity of a fuse, the cut-off value of current does not count. It is credited with the ability to clear faults equal to the prospective current (the r.m.s. value of the alternating component), so that in the case noted above, where an 800 ampere fuse cut-off at 21,500 amperes, it would be credited with a breaking capacity of 30,000 amperes r.m.s.

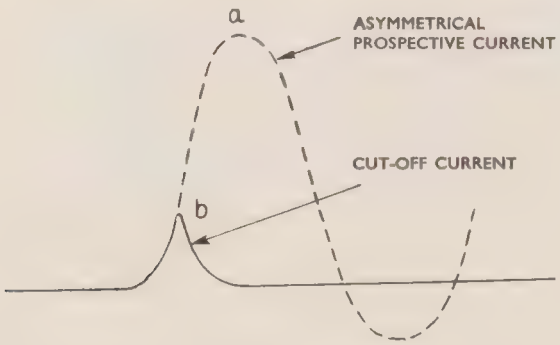


FIG. 11-8.

An interesting test on a 30-ampere fuse is shown in Fig. 11-10. This is an oscillogram of a short-circuit test with a prospective fault of 42 MVA. The appropriate values determined from this oscillogram are :—

Applied voltage	532 V.
Rec. Voltage at 0·02 sec. ..	460 V.
Prospective current r.m.s. ..	54,900 A.
Prospective current peak ..	117,200 A.
Cut-off	2,100 A.
Circuit Clearance Time ..	0·0025 sec.
Power Factor	0·22.

It is noted from Fig. 11-9 that the smaller the fuse rating the lower the cut-off current ; this is illustrated better in Fig. 11-11. Values of cut-off current are affected also by other factors such as the degree of asymmetry and whether the short-circuit is initiated on a rising or falling voltage, and will certainly vary with different makes of fuse. For any given make the appropriate values should be obtained from the manufacturer.

The feature of cut-off is, however, of great importance in switchgear incorporating fuses. Their use has led to such a considerable simplification of switchgear that the more expensive class of circuit-breaker, whether of

*Figs. No. 11-9, 11-10, 11-12, 11-26, 11-28, 11-29 and 11-31 *are reproduced by permission from a paper by the Author which appeared in the "Journal of The Institution of Electrical Engineers," see Bibliography.*

the oil or air type, capable of clearing fault currents equivalent to 25 or 30 MVA, can be dispensed with in many systems of protection. That this is so can be explained by considering the duty imposed not only on the circuit-breaker *but on all associated apparatus, e.g.*, current transformers, trip coils, busbars and connections, if this has to deal with currents of the

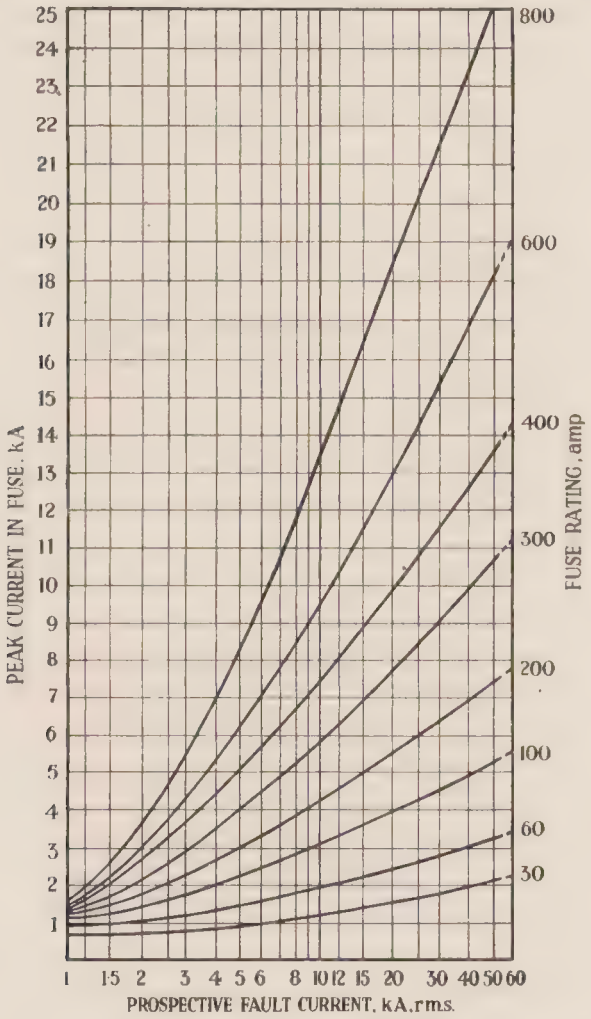


FIG. 11-9.—*Illustrating Typical Cut-off Values in a Cartridge Fuse ("Journal I.E.E.").*

order of those related to Fig. 11-10, *i.e.*, 54,900 amperes r.m.s. (117,200 amperes peak) which is so in the case of unfused gear; whereas if fuses are incorporated, the peak current to which the switchgear is subjected is only that of the cut-off, in this case 2,100 amperes. These values illustrate only a part of the easement because the electromagnetic forces due to the fault

are proportional to the *square* of these values. The author has provided considerable information on the benefits due to the use of fuses in a paper* read before the Institution of Electrical Engineers.

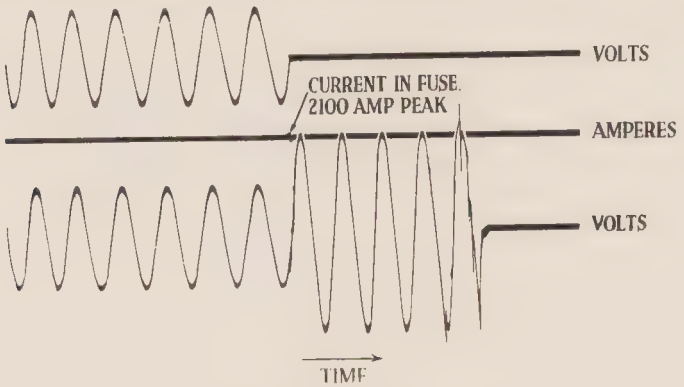


FIG. 11-10.—*Oscillogram of Test on 30 amp. Fuse ("Journal I.E.E.").*

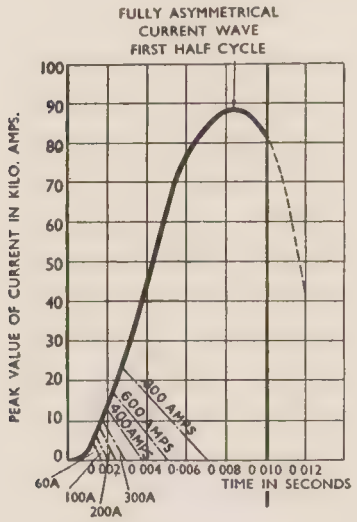


FIG. 11-11.—*Curve of fully asymmetrical current wave equivalent to 25 MVA at 440 volts.*

An equally important feature of the fuse is the safeguard it provides when closing a switch or circuit-breaker on to a faulty circuit. Considerable attention has been directed towards the danger of this operation and in recent editions of oil circuit-breaker Specifications, certain recommendations have been made suggesting that when the fault current exceeds 10 kA r.m.s. (symmetrical breaking current) some form of power-operated closing

*See Bibliography.

device shall be used. The now common fault value of 25 MVA at 400 volts means a fault current of 36 kA, but economic considerations rule out the use of a power closing device, *e.g.*, spring or solenoid, on medium voltage switchgear.

An alternative is suggested in the relatively new device described as a "making-current release." This is defined as a device which "during a closing operation, causes a trip-free circuit-breaker to open automatically

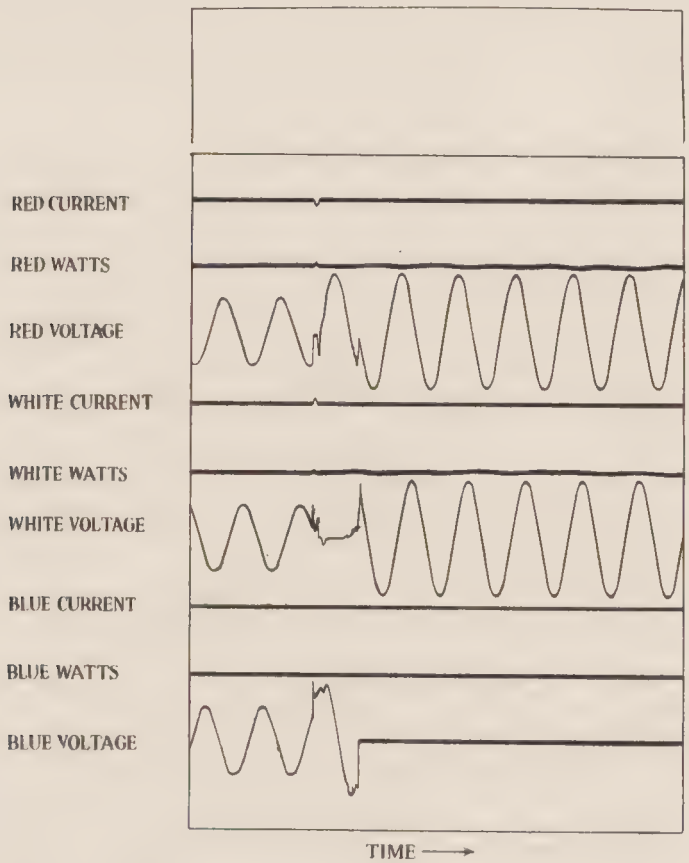


FIG. 11-12.—*Oscillogram of 3-Phase Make-Break Test on Air Circuit-Breakers with Fuses ("Journal I.E.E.").*

and without intentional time delay when the making-current exceeds a predetermined value." Making-current releases to achieve this object have been evolved in both mechanical and electrical types (see also Chapter XIV) and M. C. Hunter has suggested that where the *extra* energy required to close against the short-circuit amounts to more than 20 per cent. of the no-load closing energy of the breaker, a making-current release is the economical solution. The h.r.c. fuse possesses complete making-current release properties in view of the cut-off feature of the fuse, a feature which

is present whether operating to clear a fault with the switch or circuit-breaker in the closed position or in closing the switch or circuit-breaker on to an existing fault.

This has been shown by short-circuit tests to be a valuable feature. Fig. 11-12 is an oscillogram of a make-break test on a three-phase circuit-breaker incorporating h.r.c. fuses.

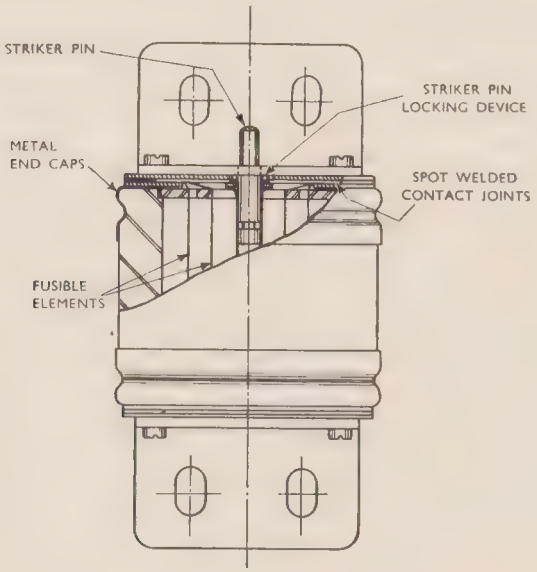


FIG. 11-13.—*Cross-section of EETEE/JP h.r.c. Fuse with tripping device (Electric Transmission, Ltd.).*

The data established by this test indicates that a current cut-off a 6 kA was obtained on a test circuit where the prospective peak making current was 96 kA.

Witlhout the fuses, the closing operation would have been made against the full peak current, subjecting the breaker and its associated apparatus to the high stresses associated with that current, instead of to those at the much lower value of 6 kA. It is indeed doubtful whether any operator could close a breaker *by hand* against the higher value.

While possessing excellent making-current release properties, the fuse has one essential difference compared to other forms of making-current release, *viz.*, it has to be replaced after each operation. The protection afforded, however, is so high as to outweigh this disadvantage.

In recent years, an h.r.c. fuse has been developed which incorporates a striker pin which functions after the fuse proper has finally cleared the fault current and in functioning trips out an associated circuit-breaker or switch. By this means, three-phase clearance of a faulty circuit is achieved if only one fuse operates and the disadvantages of single-phasing are avoided.

Fig. 11-13 shows a typical cross-section of the tripping fuse while

Fig. 11-14 is an elementary diagram to illustrate the principal. From these illustrations, it is noted that the striker pin is carried in a small cylinder within the fuse body. Behind the striker there is a small chemical charge, suitably sealed off. From the striker pin, a shunt wire of high resistance tungsten is taken, passing through the charge and thence to the opposite end cap. At the point where this wire passes through the chemical charge, a weak link is introduced.

On the occurrence of a fault, the silver elements melt first and the fault current is transferred to the shunt wire.

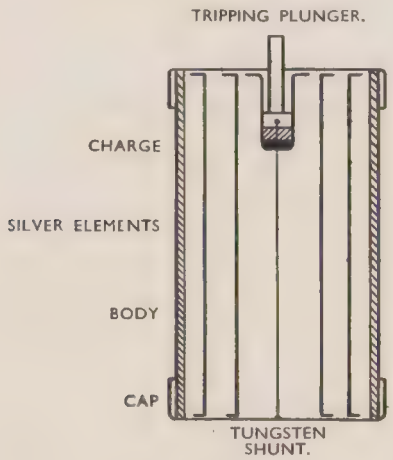


FIG. 11-14.—*Elementary Section of Fuse with tripping device (Electric Transmission, Ltd.).*

The weak section of this is heated causing the charge to be fired and the striker pin is forced outwards. A limit is placed on the movement of the striker pin so that it is not ejected bodily from the fuse body, and at the same time, the limiting feature prevents the striker pin being pushed back by hand or by attempts to reclose the breaker. This provides a free-handling feature on the circuit-breaker as the trip bridge is held in the " trip " position.

The high resistance of the tungsten shunt wire acts to prevent harmful overvoltages after fault clearance, acting in a manner similar to that of resistance switching in air-blast circuit-breaker practice (see Chapter X).

In addition to circuit-breaker tripping, this type of fuse can be used to cause an alarm to be given, trip out a remote circuit-breaker (*e.g.*, the d.c. circuit-breaker on rotary convertor or rectifier circuits) or to de-energise the hold-on coil of a contactor.

The h.r.c. fuse, whether non-tripping or tripping type, has many applications in switchgear practice. The most popular application is undoubtedly the ordinary switch-fuse or fuse-switch. Many examples of this exist and one has been illustrated in Chapter VI. Another application is in the " skeleton " type of distribution board, also described in Chapter VI. In these applications the non-tripping type of fuse has been used. More recently, and because of the development of the tripping fuse, a new design

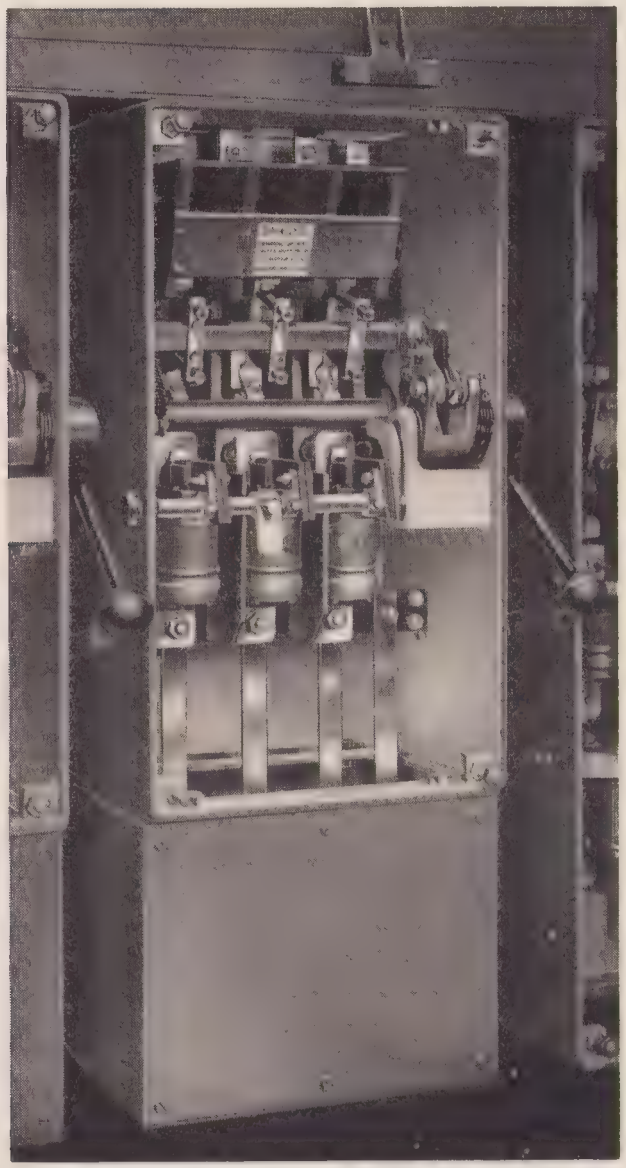


FIG. 11-15.—*Air-Break Circuit-Breaker with Back-up Fuses (J. & P., Ltd.).*

of circuit-breaker has been produced using the fuse as the basis of design for fault clearance, with the circuit-breaker to take care of load and overload switching. This new design has considerable economical advantages over a circuit-breaker designed to take care of fault clearance without the aid of fuses, while, because of the tripping fuse and the facility of a trip bridge to unlatch the circuit-breaker, it has all the advantages of other types, plus making-current release features.

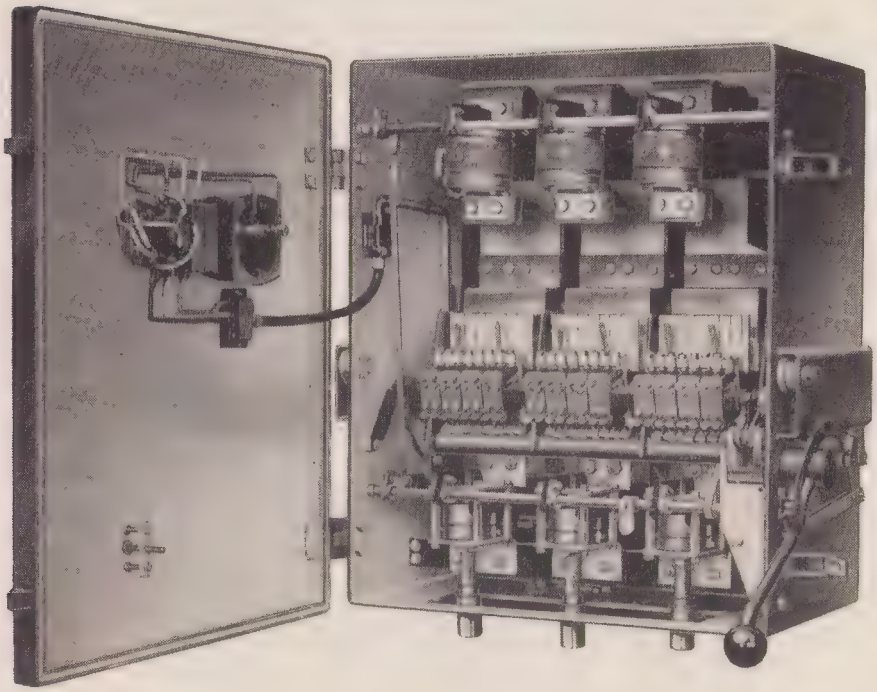


FIG. 11-16.—*Air-Break Circuit-Breaker with fuses and overload coils (J. & P., Ltd.).*

This new design is air-break, and typical examples of its construction are shown in Figs. 11-15 and 11-16; the former showing a unit with fuses only, the latter a unit with fuses and overload trip coils. A modification of the design enables it to be used for motor-starting circuits, the unit shown in Fig. 11-17 being typical. Here in addition to fuses and overload trips, a no-volt no-close feature is provided. As shown in Chapter VI, circuit-breakers of this type have been designed on the fixed principle, *i.e.*, no means of isolation and on the draw-out principle giving double isolation.

In addition to the use of tripping fuses in the specially designed air-break circuit-breakers described above, they have been used effectively to back-up ordinary industrial circuit-breakers.

Typical examples of this application are shown in Figs. 11-18 and 11-19, the former showing how two fuses per phase are used in parallel where the normal current of the circuit is beyond the available fuse rating. As in the air-circuit breaker, the fuse striker pins operate to trip out the circuit-breaker and lock it out until the fuse is removed.

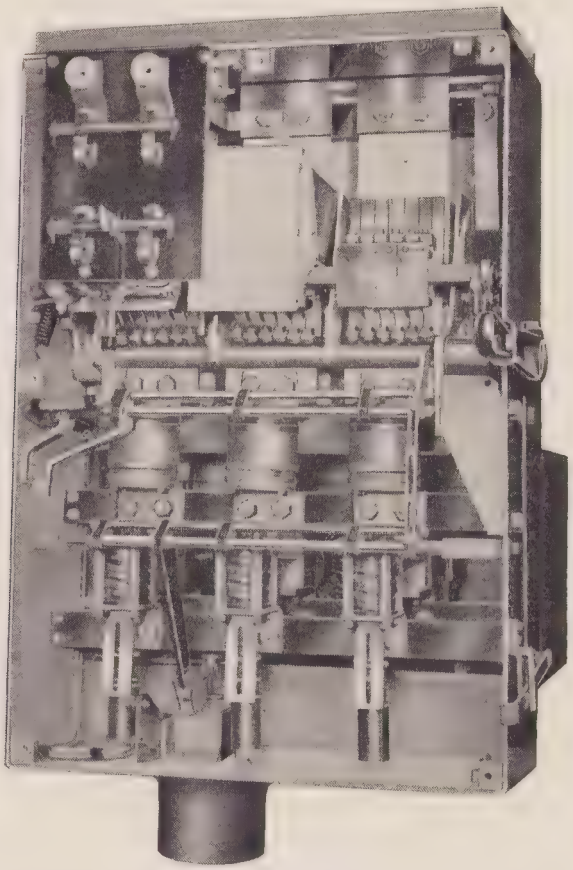


FIG. 11-17.—*Air-Break Circuit-Breaker with Tripping Fuses, Overload Trips, and No-Volt No-Close Device for Motor Starting (J. & P., Ltd.).*

Circuit-breakers, both air and oil, of the types described, have been short-circuit tested on an A.S.T.A. test plant and details below relate to the tests on a 60-ampere air-break circuit-breaker.

The basis of the tests is that in B.S.936 for low-voltage oil circuit-breakers. This basis was chosen in the absence of any specification specifically covering the new type of switchgear and because it covers circuit-breakers for use in electrically remote situations such as those in which the new air-break circuit-breaker would most frequently be used. The test duties involved are :—

(1) B-MB at 30% of the rated breaking-current.
(2) B-MB at not less than 100% of the rated breaking-current.

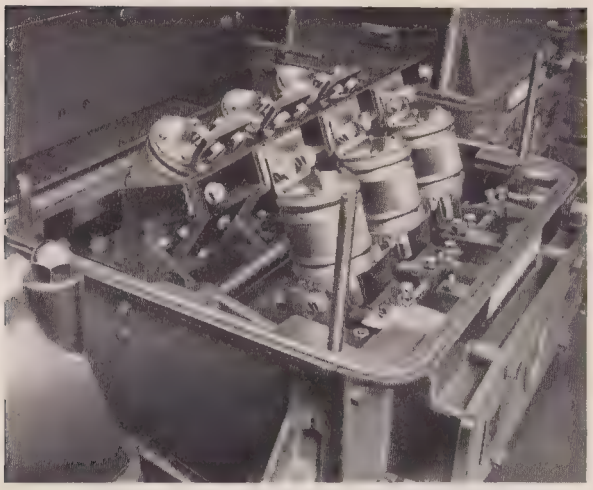


FIG. 11-18.—*Back-up Tripping Fuses in parallel* (2×500 *amps.*) *mounted on oil circuit-breaker* (*J. & P., Ltd.*).

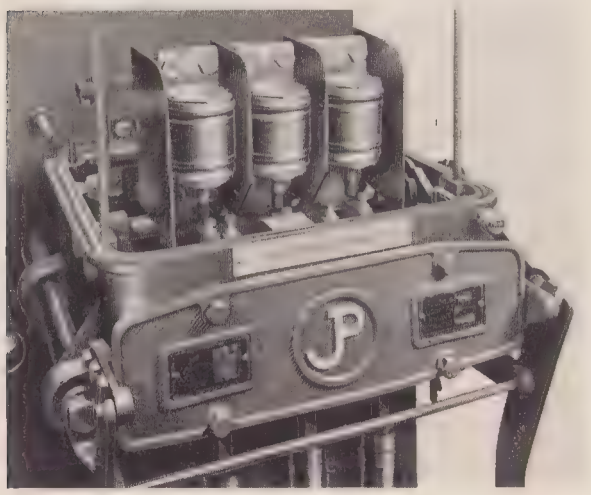


FIG. 11-19.—*Back-up Tripping Fuses* (300 *amps.*) *mounted on oil circuit-breaker* (*J. & P., Ltd.*).

Because of the cut-off feature of the fuses a calibration test to determine the prospective current had to be made before each of the tests (1) and (2). The rating assigned to the combination is :—

Breaking capacity at 440 v.	=	40 kA r.m.s.
Making capacity at 440 v.	=	80 kA peak.

Based on this assignment, the 30% calibration test on the circuit set-up gave the following results, obtained from the oscillogram, Fig. 11-20.

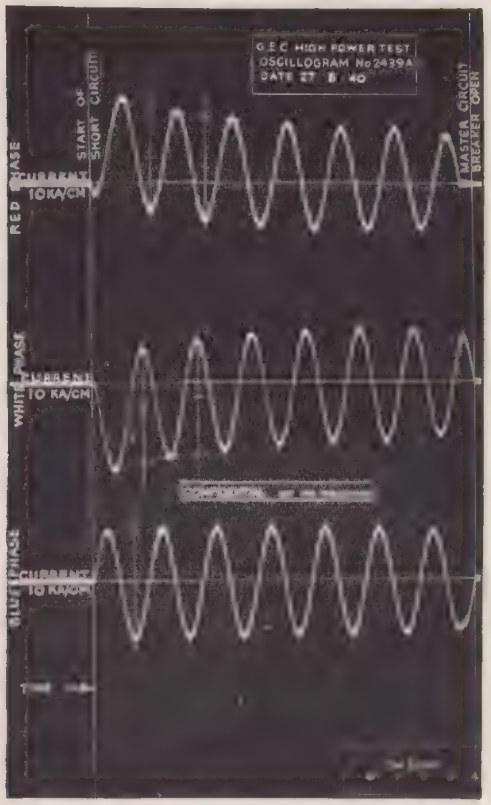


FIG. 11-20.

	R.	W.	B.
Peak kA in 1st major loop	31·0	32·6	21·3
Peak a.c. component, kA	19·5	21·3	20·2
R.M.S. value of a.c. component, kA..	13·8	15·1	14·3
Average kA r.m.s.		14·4	
Power factor		0·0796	

The test duty (1) at 30% of rating is shown in Figs. 11-21 and 11-22, the former being a "B" operation, the latter an "MB." The analysis of these oscillograms shows that the fuses operated to clear the short-circuit at the cut-off values :—

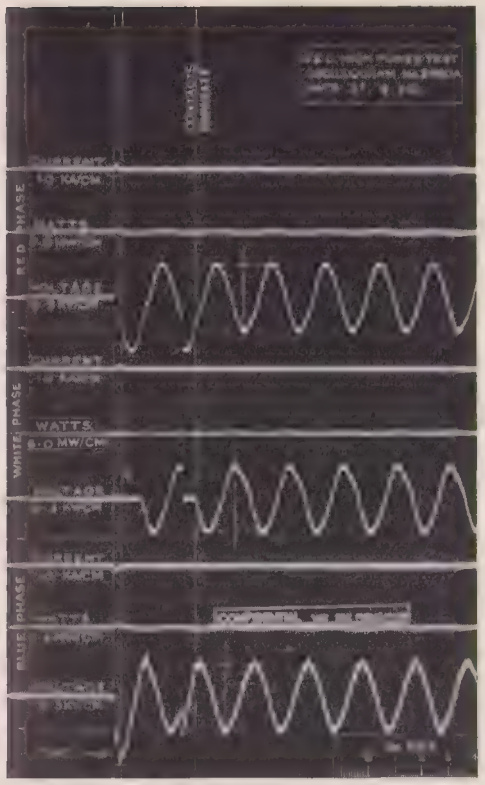


FIG. 11-21.

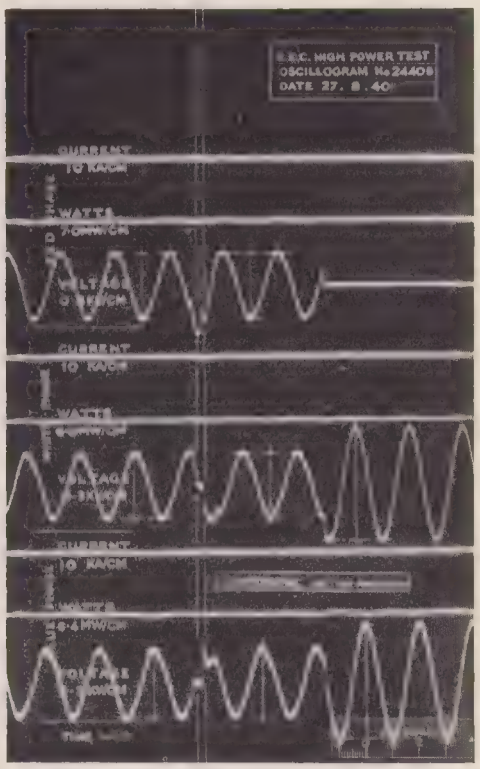


FIG. 11-22.

		R.	W.	B.
Fig. 11-21	kA	2·2	1·2	2·0

with an arc duration of 0·28 half-cycles ;

		R.	W.	B.
Fig. 11-22	kA	—	1·0	1·0

with an arc duration of 0·26 half-cycles.

The 100% calibration test, shown in Fig. 11-23, gives the following results on analysis.

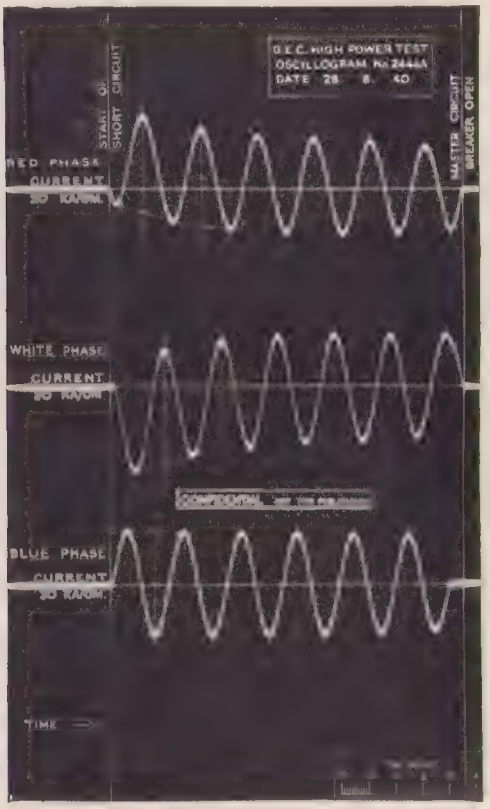


FIG. 11-23.

	R.	W.	B.
Peak kA in 1st major loop	81·0	96·0	60·5
Peak a.c. component kA	53·8	63·8	57·8
R.M.S. value of a.c. component kA ..	38·0	45·1	40·9
Average kA r.m.s.		41·3	
Power factor		0·1225	

The test duty (2) at 100% of rating is shown in Figs. 11-24 and 11-25, being "B" and "MB" operations respectively. The analysis of these oscillograms shows that the fuses operated to clear the short-circuit at the cut-off values :—

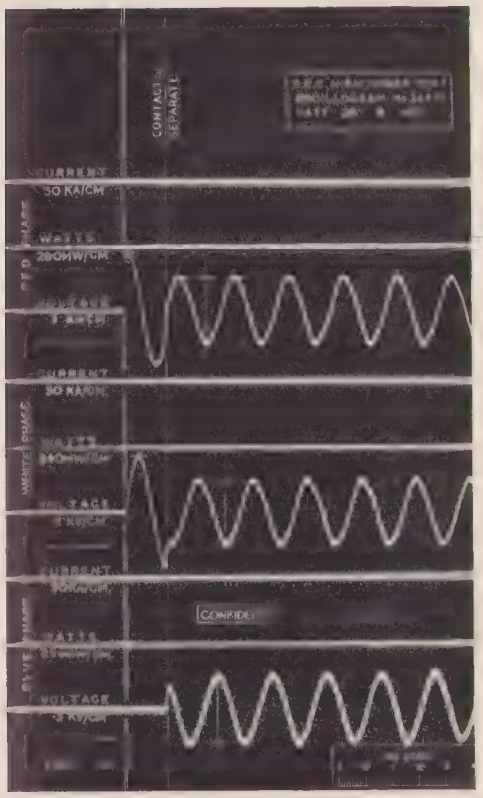


FIG. 11-24.

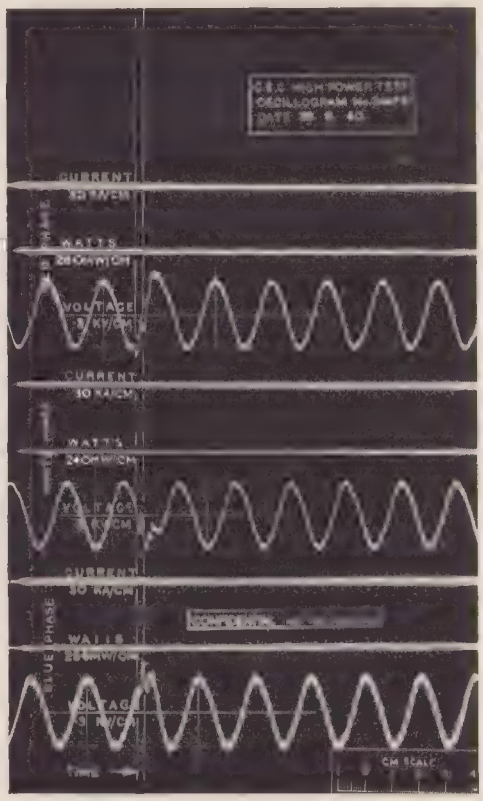


FIG. 11-25.

		R.	W.	B.
Fig. 11-24 .. .. .. kA		3·5	3·0	Trace

with an arc duration of 0·1 half-cycles ;

		R.	W.	B.
Fig. 11-25 .. .. .. kA		1·5	1·5	2·0

with an arc duration of 0.26 half-cycles.

This series of tests adequately emphasise the cut-off feature of h.r.c. fuses, for example, in the 100% tests :—

Phase	Prospective Current Peak kA	Cut-off Current kA
R	81·0	1·5
W	96·0	1·5
B	60·5	2·0

In a further series of tests on a 600 ampere circuit-breaker and fuse combination, with the test circuit giving the same values of prospective current, the results were :—

R	81·0	6·0
W	96·0	6·0
B	60·5	No current carried

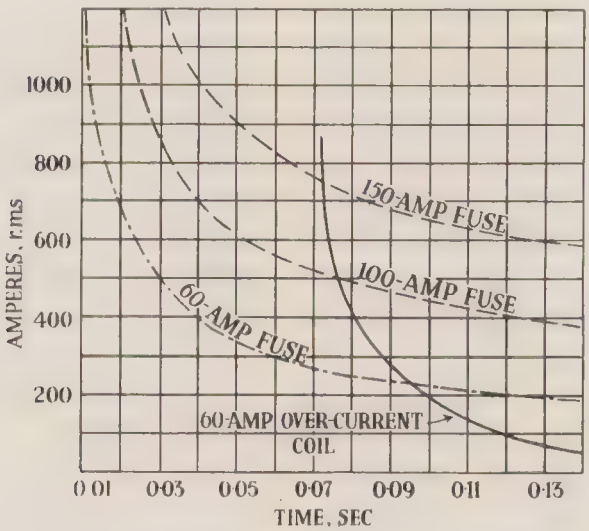


FIG. 11-26.—*" Take-over " Curves (" Journal I.E.E.").*

Considerable controversy occurs over the problem as to whether the h.r.c. fuse should be used to provide overload protection in addition to short-circuit protection. In general, it is desirable that the fuse be installed simply for short-circuit protection, and if overload protection is required, it should be provided by means of separate devices.

In this case, due cognizance must be taken of the fact that at some value of current *greater* than the normal rating of the circuit-breaker the fuse will be slower in operation than the trip coil.

This is illustrated in Fig. 11-26 which shows the characteristic curves of three typical fuses together with that of a 60 ampere overload coil. It is clear that at currents below the points of intersection, *i.e.*, 220, 500 and 750 amperes respectively, the circuit-breaker must clear these currents *without* aid from the fuses, and proof should be obtained that this can be achieved. In practice, it is possible that a circuit-breaker may have 60 ampere

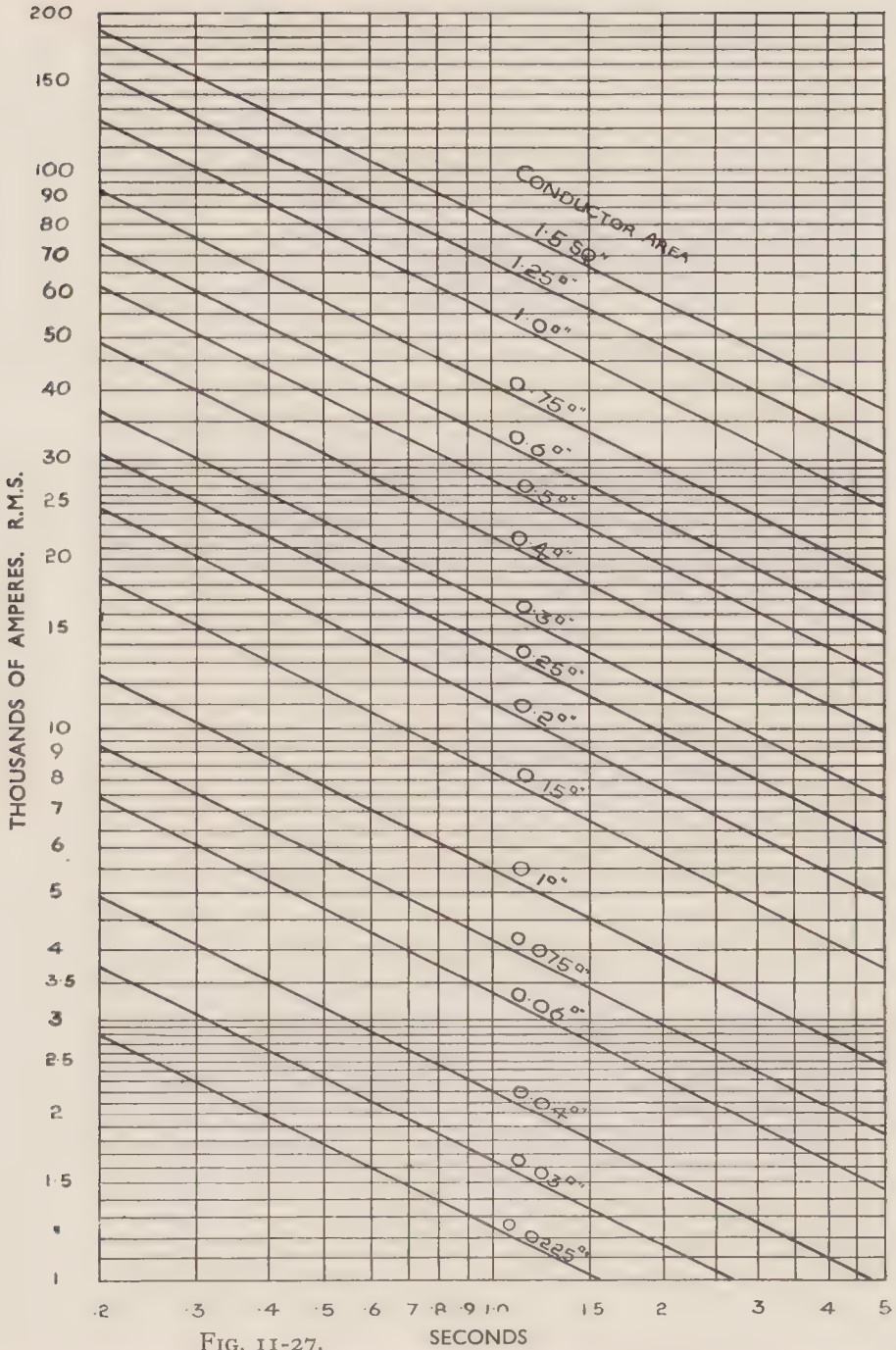


FIG. 11-27.

Curves showing short-circuit current against time for various cable sections.
(*"Distribution of Electricity."—W. T. Henley's Telegraph Works, Ltd.*)

coils, with 100 or even 150 ampere fuses to take care of the current rush on motor starting. Thus a 60 ampere circuit-breaker may be called upon to clear currents up to 750 amperes.

In the author's I.E.E. paper previously referred to, attention has been drawn to the protection h.r.c. fuses provide for associated apparatus. In particular, the protection given to cables of small section may be noted. Data published on the short-time rating of cables do not give current values for very short-times, the lower limit noted being usually 0.2 sec. This time may be taken as that necessary for the majority of circuit-breakers with instantaneous protection to operate in order to clear the circuit. Even on the smallest circuits, where only small cables are necessary on a normal current basis, the fault current may be high, being determined by the system and *not* by the capacity of the individual circuit.

Fig. 11-27 gives a family of curves of short-circuit current against time for various cable sections. For example, a cable of 0·0225in.^{2} section is given a short-time rating of under 3 kA r.m.s. for 0·2 sec. If such a cable is used on a circuit which is tied to a system where the fault MVA is 25, then the symmetrical r.m.s. fault current is approximately 36 kA, or 12 times the value which the cable can withstand for 0·2 sec.

Where h.r.c. fuses are used as protective devices, the cut-off current is the limiting value and as has been shown in Fig. 11-9, this is as low as 3·2 kA for a 60 amp. fuse and 5 kA for a 100 amp. fuse, figures more in line with the limiting value for the cable.

Cables may be damaged in two ways by short-circuit currents, namely thermally and mechanically. In the first case, the conductor may be raised to a dangerously high temperature or may even melt. Insulation may be damaged sufficiently to render the cable unsafe for further use. In the second case, the high bursting stresses may damage the cable or cause serious trouble at the joint boxes.

In all applications it is important, if the h.r.c. fuse is to give the service intended, that careful thought be given to the selection of a suitable rating. Haphazard selection has often led to condemnation quite undeservedly. In general, there are two types of load—steady and fluctuating. In the first the usual practice is for the fuses to be the only protection in the circuit, and in this case, the fuse rating can be the standard equal to or next greater than that of the circuit, or of the apparatus, whichever is the smaller. Close selection to the circuit rating is not of paramount importance if short-circuit protection only is desired. For example, for a full load current of 145 ampere, a natural choice of fuse rating might well be 150 amp. With a symmetrical fault current of 5 kA, such a fuse would clear in approximately 0.01 sec. If instead, a 200 amp. fuse is selected for the same fault current the clearance time would be about 0·015 sec. If full-load conditions exist normally on the circuit, the 150 amp. fuse would be running within 5 amp. of its full rating, whereas the 200 amp. fuse would have a good 25 per cent. in hand. In consequence, the larger fuse will run cooler and have a longer life as well as a margin in hand for some temporary overload without risk of deterioration. These advantages are gained at the cost of a difference in fault clearance time of 0·005 sec. In selecting fuses on this basis, due note must be taken of discrimination problems if they arise. If overload protection is also provided, by coil or other means, fuses of still greater rating may be permissible or necessary.

The selection of fuses for fluctuating loads is more difficult. The best method is to submit full details of the circuit characteristics to the manu-

facturer of the fuses so that he may recommend on the basis of his experience. In general, the fuses should have time/current characteristics such as to allow the transient over-current to be carried without deterioration, this usually involving a fuse rating greater than the current-rating of the circuit. The most familiar form under the definition of a fluctuating load circuit is the motor circuit.

Here it is essential that particulars be available of the magnitude and duration of the starting-current from the motor manufacturer. With this

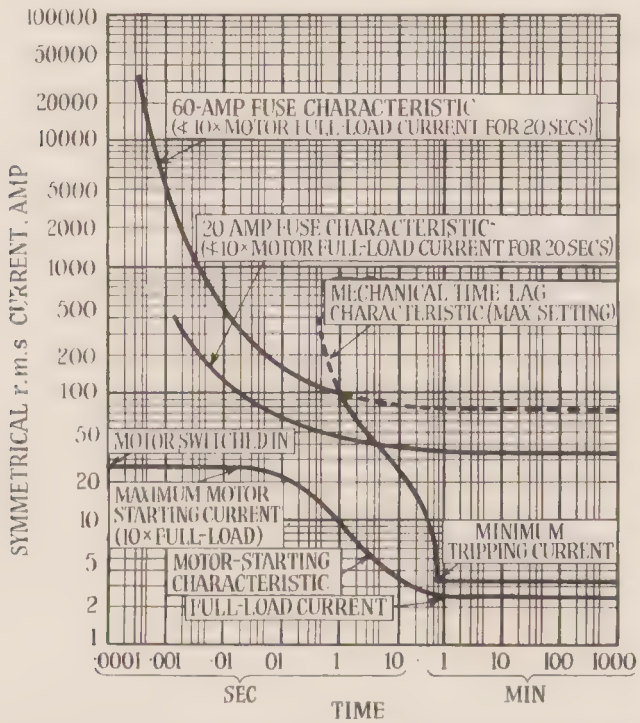


FIG. 11-28.—*Curves showing Motor-Starting Characteristic and Fuse Characteristics ("Journal I.E.E.").*

information a fuse must be chosen whose time/current characteristic lies above that of the motor starting characteristic, with an adequate margin, as shown in Fig. 11-28.

It is important that there shall be an adequate gap between the knee of the motor starting characteristic where the starting current begins to fall to its full-load condition, and the curve of the fuse characteristic adjacent to this knee. What this gap should be depends on the type of drive, *i.e.*, taking into account the possibilities of stalling, etc. A guide in this direction is given under Useful Data for one type of fuse.

Capacitor, transformer and fluorescent-lighting circuits are other examples of fluctuating load circuits. For these, fuses usually have current-ratings about 50 per cent. greater than the normal current of the apparatus to be protected. This is a rough guide as much depends on the time/current

characteristics of the fuses and here again reference to the maker is most desirable. Capacitor circuits are particularly difficult because, at switching-in, a current surge of a high transient nature occurs. The peak value of this current can be very high and it can have a high natural frequency. The period during which this condition exists is very short and the transient is usually damped rapidly, the current reaching normal in about 0·02 sec.

One fuse manufacturer makes the following recommendations for fuse ratings on capacitor circuits:

Capacitor reactive power at 400 v. kVAr	F.L. Current A	Fuse rating A
50	72	125
100	144	250
200	288	400
300	432	600

which approximate to the 50 per cent. recommendation above.

With all types of fused-switchgear, there is an ever present danger that on a line-to-earth fault there will be insufficient current in the fault to cause operation of the fuse in the faulted line. The high resistance of the earthing system is responsible for this condition. In low voltage systems we have only about 230 volts impressed across this resistance and if, as is often the case, the ohmic value of the earthing system is 2 ohms or more, a current not exceeding 115 amps. will flow to earth.

This is the current available to operate the line fuse and an examination of the characteristic curves of most h.r.c. fuses will show that for any fuse above 60 amp. operation will not occur due to a current of 115 amps. This has been shown in Appendix B.

It is therefore vital that the resistance value be the lowest obtainable and *that it be maintained at a low value.* A resistance of one ohm, for example, will double the available current. If an earth fault occurs and operation does not result, then the fault may persist until (*a*) such time as the fuse clears owing to deterioration by carrying some excess current for a very long period (an unsatisfactory condition for good fuse performance) or (*b*) the fault converts itself into one between lines *i.e.*, a phase fault. In the meantime a dangerous condition has existed which may lead to fire owing to overheating.

Attention has been directed to the unsuitability of fuse gear due to the foregoing, particularly in certain circumstances such as mines or other locations where earth faults are dangerous. In those types of switchgear where the tripping fuse is used, the existence of means of tripping the switch or circuit-breaker makes it possible to use an earth fault relay operated from a conventional core-balance current transformer, and the relay contacts operate to close the circuit to a shunt trip coil, which in turn operates on to the trip bar. Such an arrangement is sound and follows established practice.

A new development* for use in fuse gear now provides earth-fault

**British Patents No. 563060 and 563849.*

protection by what is described as an " earth-fault striker," which in external appearance is similar to a fuse and no more costly. Like the relay, it needs a core-balance current transformer in the primary circuit.

The " striker " is connected in the secondary circuit in the same way as the relay. This new device has been evolved from the tripping fuse, and is, in effect, the striker portion of that fuse but calibrated because it has to protect as well as trip.

A typical " striker " is shown in cross-section in Fig. 11-29. It has no main-current elements and operation is dependent on heating and not fusion. A short heating element (A) is suspended between two low-resistance leads (B); it has a high specific resistance being wholly embedded in a small chemical charge. The temperature setting of the charge is related to the section of the element in such a way that the striker operates at definite current values within definite time limits. The relation between current and time can be represented by an inverse time/current characteristic.

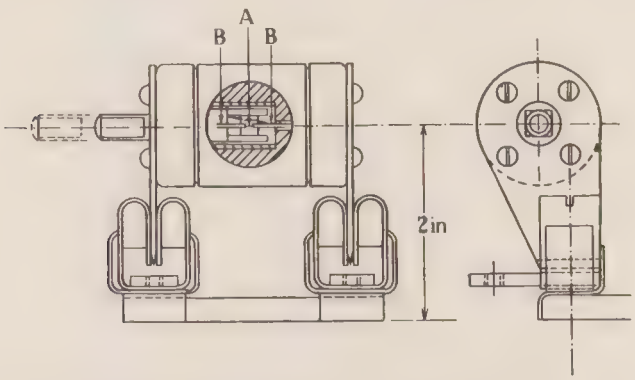


FIG. 11-29.—*Earth-fault Striker (" Journal I.E.E. " and Electric Transmission, Ltd.) (Patent No. 563849).*

This is important in that an earth fault does not need to be of a prescribed magnitude to cause operation, as required by the fixed setting of a relay. The small fault will cause operation in the time necessary to heat the element to the temperature sufficient to fire the charge. A higher fault value causes immediate operation.

The degree of sensitivity depends largely on the primary current but for values above 100 amps. in the primary circuit, instantaneous tripping has been achieved at values of $7\frac{1}{2}$ per cent. earth fault. In general, 15% earth fault tripping is acceptable.

Fig. 11-30 shows the earth fault striker applied to an air-break circuit-breaker as described earlier.

The protection of a motor circuit is incomplete unless the protective gear also takes care of the possibility of an open-circuit on one line. The most common causes of open-circuits are poor contact on one pole of a starter in the delta position, poor contacts at a fuse, deterioration of an incorrectly selected fuse owing to frequent starts leading to ultimate operation of the fuse, and, of course, earth faults where there is sufficient current to operate one main fuse of the non-tripping type.

It has been shown that with an open-circuit on one line, excess current exists in the two healthy lines and in the motor windings.

Under full-load conditions, the currents in the two healthy lines may be as much as 2·43 times normal, while two of the motor windings may

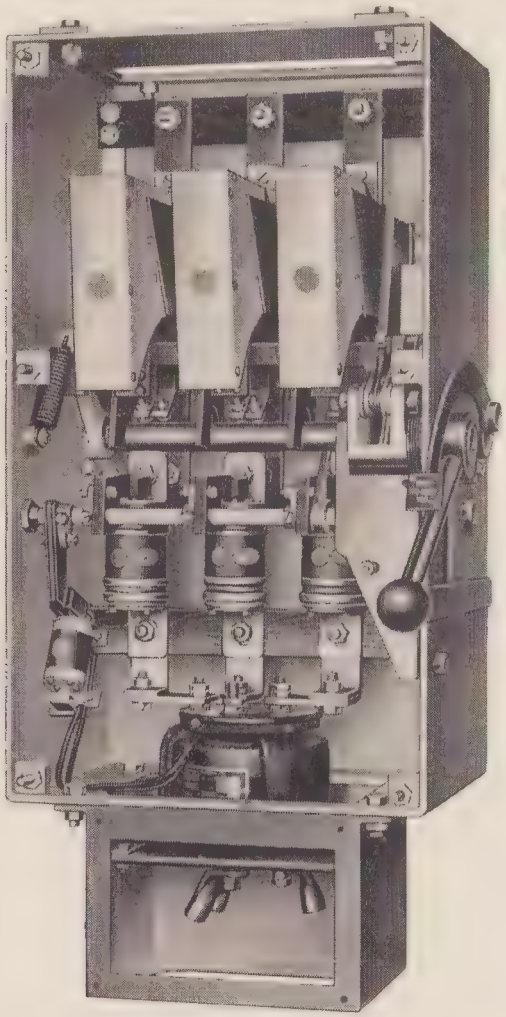


FIG. 11-30.—*Air-break Circuit-Breaker with main fuses and earth fault striker* (*Patent No.* 563060) (*J. & P., Ltd.*).

carry 1·28 times, and the third 2·82 times, the normal current. Thus, if we assume a 40 h.p. motor of the squirrel-cage type, 400 volts, 3-phase with a full-load current of 56 amps., and in which the standstill current may be of the order of 400 amps., we would, for adequate protection use

fuses having a normal rating of 150 amps. Under conditions of open-circuit, the two healthy lines will carry 2·43 times normal, *i.e.*, 136 amps., a current clearly insufficient to cause operation of a 150 amp. fuse.

The condition of open-circuit can be taken care of by the use of the " striker " described for earth-fault protection. In this case, three small single-phase voltage transformers are used, connected as shown in Fig. 11-31. As will be seen, the striker is connected to complete the delta circuit

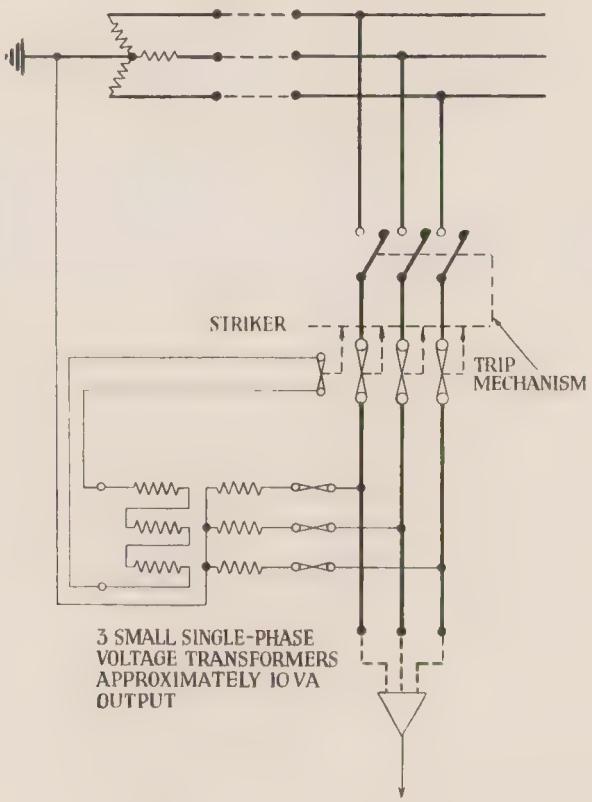


FIG. 11-31.—*Open-circuit Protection (" Journal I.E.E.").*

of the secondary windings. The transformers may be of the type used for toy electric trains, bells, or low-voltage lighting, with a secondary voltage of say 12 volts.

An application for h.r.c. fuses of the tripping type is that where they are used in series with contactors. The latter have not a high breaking-capacity and must therefore be provided with other means of protection against faults when these are of the order of 25 MVA or more. Fig. 11-32 shows one panel of a power station auxiliary board where contactors are used in conjunction with tripping fuses.

Here the fuse operates to act on to a bar which actuates a set of auxiliary contacts which in turn open the hold-on coil circuit and closes the trip coil

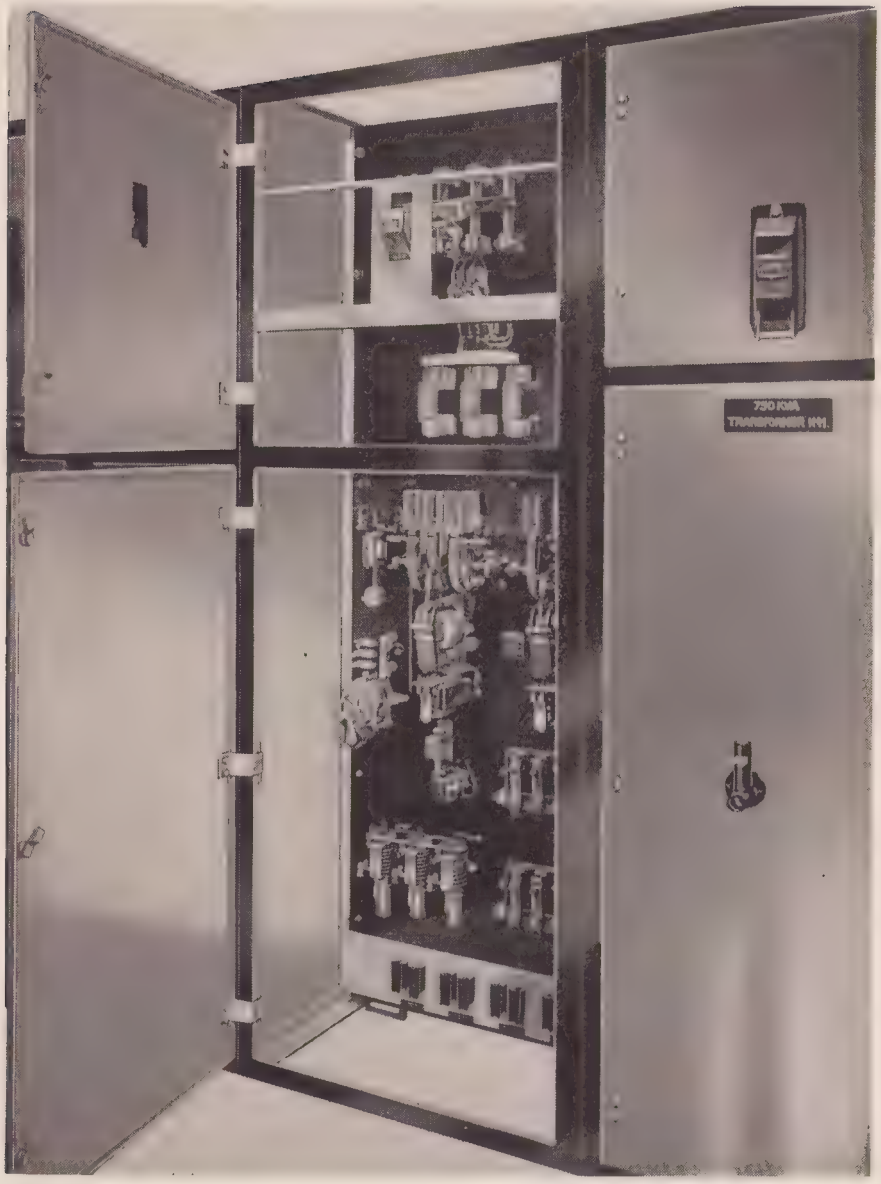


FIG. 11-32.—*Control Cubicle for Power Station Auxiliaries, with fuses backing up contactor (J. & P., Ltd.).*

circuit of the contactor. The diagram for this arrangement is shown schematically in Fig. 11-33.

Some dislike exists to the use of fuses on the score of renewal expense. This usually can be traced to incorrect and haphazard selection. Given

the correct fuse for the application, the fuse provides one of the best fault clearance devices at low cost, and renewals on a well maintained system should be few and far between.

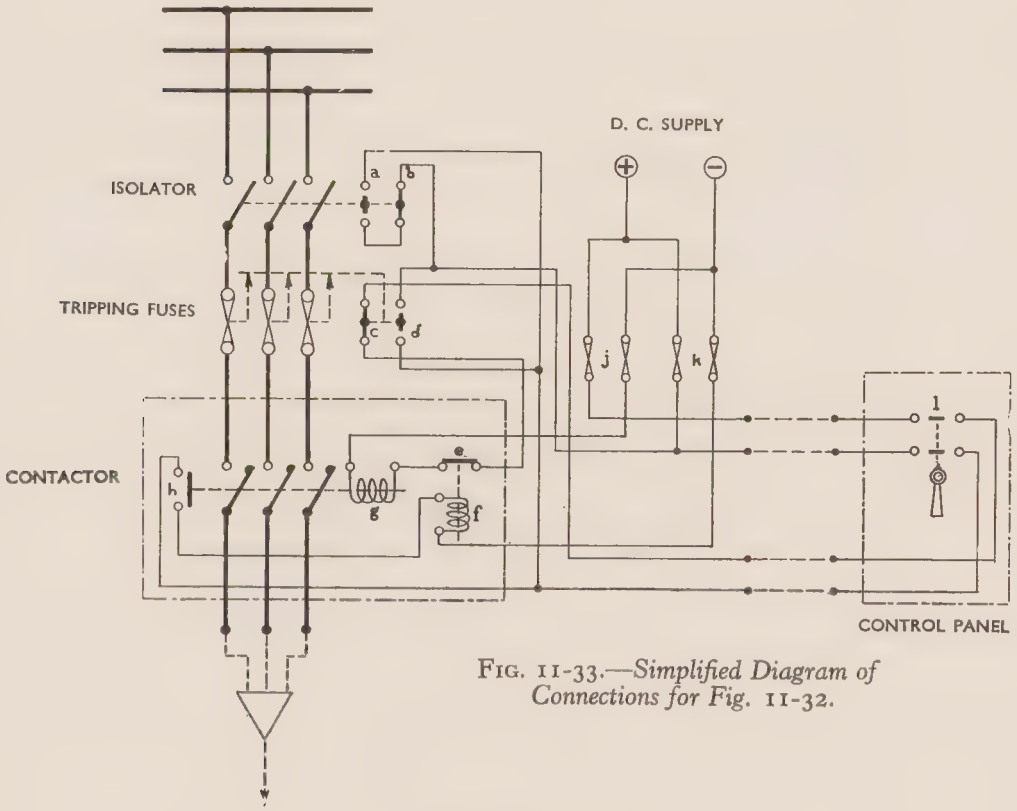


FIG. 11-33.—*Simplified Diagram of Connections for Fig.* 11-32.

SYMBOLS.

a — Isolator Auxy. SW. — Makes before Isolator closes. Open when Isolator is open.
b — Isolator Auxy. SW. — Makes before Isolator opens. Open when Isolator is closed.
c — Trip Bridge Auxy. SW. — Closed when Fuses intact. Opens when Fuse operates.
d — Trip Bridge Auxy. SW. — Open when Fuses intact. Closes when Fuse operates.
e — Trip Coil Auxy. SW. — Normally closed. Opens when trip coil energised.
f — Contactor Trip Coil.
g — Contactor Closing Coil.
h — Contactor Auxy. SW. — Open when Contactor open.
j — Fuses—Closing circuit.
k — Fuses—Tripping circuit.
l — Control Switch—Trip and Close.

BIBLIOGRAPHY.

"The Fuse—1896/1941," W. E. Bradshaw, "Electrical Times," 1941, page 406, No. 99.

"The High-Rupturing-Capacity Cartridge Fuse, with Special Reference to Short-Circuit Performance," J. W. Gibson, "Journal I.E.E.," 1941, No. 88, Part II, p. 2.

"Fuses v. Circuit-Breakers," G. Cluley, "Electrical Review," 1943, No. 132, p. 143.

"Earth-Leakage Protection, Application to Fused Switchgear," K. Dannenberg and R. T. Lythall, "Electrical Review," 1944, No. 135, p. 113.

"Excess-Current Protection by H.R.C. Fuses on Medium-Voltage Circuits," R. T. Lythall, "Journal I.E.E.," 1945, No. 29, Part II, Vol. 92, p. 419.

"Excess-Current Protection by Overcurrent Relays on Medium-Voltage Circuits," A. G. Shreeve and P. J. Shipton, "Journal I.E.E.," 1945, No. 29, Part II, Vol. 92, p. 430.

"Force-Trip Devices: A Field for the High-Rupturing-Capacity Fuse," R. T. Lythall, "Electrical Review," 1941, No. 128, p. 545.

"Oil-less Metalclad Switchgear for a.c. Circuits up to 660 Volts 3-Phase," H. E. Cox and L. Drucquer, "Journal I.E.E.," No. 527, Vol. 87.

Switchgear Handbook, Vol. 1, W. A. Coates and H. Pearce (Pitman and Sons).

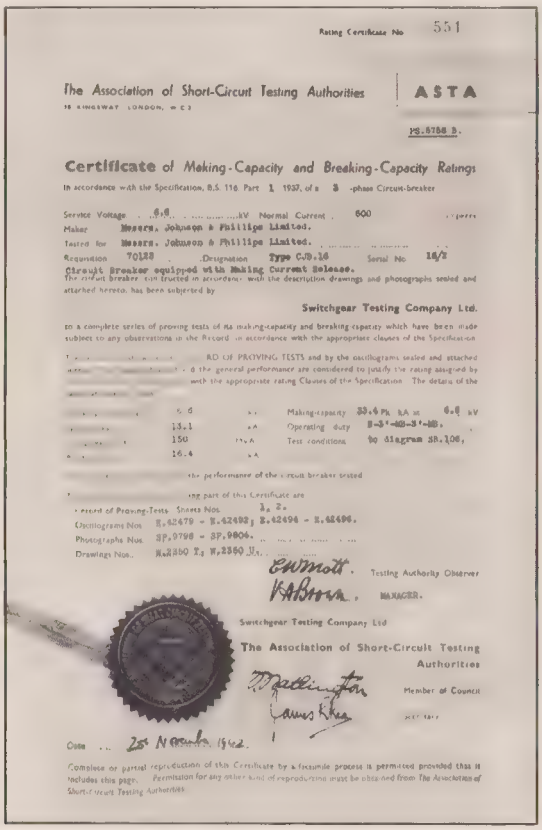
B.S. 88-1947. "*Electric Fuses, Low Voltage and Medium Voltage.*"

"The H.R.C. Fuse and its place in Industrial A.C. Systems," R. T. Lythall. "The Mining Electrical & Mechanical Engineer," July, 1948, Vol. 29, P. 7.

CHAPTER XII

SHORT-CIRCUIT TESTING AND THE EVALUATION OF ELECTROMAGNETIC OSCILLOGRAMS

In days gone by, the short-circuit rating assigned to a given circuit-breaker or fuse by the manufacturer depended on the general knowledge of the designer, the behaviour of similar devices in service, the early researches of the E.R.A., certain empirical formula for which little authority could be



Rating Certificate No 551

The Association of Short-Circuit Testing Authorities
18 KINGSWAY LONDON, W.C.2

ASTA

PS.5788 B.

Certificate of Making-Capacity and Breaking-Capacity Ratings

In accordance with the Specification, B.S. 116 Part 1 1937, of a 3 -phase Circuit-breaker

Service Voltage 6.6 kV Normal Current 600 Amperes
Maker Messrs. Johnson & Phillips Limited.
Tested for Messrs. Johnson & Phillips Limited.
Requisition 70128 Designation Type CJB.16 Serial No 16/2
Circuit Breaker equipped with Making Current Release.
The circuit breaker constructed in accordance with the description drawings and photographs sealed and attached hereto, has been subjected by

Switchgear Testing Company Ltd.

to a complete series of proving tests of its making-capacity and breaking-capacity which have been made subject to any observations in the Record in accordance with the appropriate clauses of the Specification

RD OF PROVING TESTS and by the oscillograms sealed and attached d the general performance are considered to justify the rating assigned by with the appropriate rating Clauses of the Specification The details of the

6.6	kV	Making-capacity	33.4 Pk kA at 6.6 kV
13.1	kA	Operating duty	B-3'-MB-3'-MB.
150	MVA	Test conditions	to diagram SB.106,
16.4	kA		

the performance of the circuit breaker tested

ing part of this Certificate are

Record of Proving-Tests Sheets Nos. 1, 2.
Oscillograms Nos. E.42479 - E.42492; E.42494 - E.42496.
Photographs Nos. SP.9798 - SP.9804.
Drawings Nos. W.2350 T; W.2350 U.

E.W.Mott. Testing Authority Observer
V.A.Brown. MANAGER.

Switchgear Testing Company Ltd

The Association of Short-Circuit Testing Authorities

Member of Council

Secretary

Date 25th November 1942.

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FIG. 12-1.—*Typical A.S.T.A. Test Certificate.*

found, and on such tests as could be carried out on commercial alternators when these were undergoing acceptance tests. To-day, the availability of specially designed test plants makes guesswork unnecessary and ratings can be assigned with an exact knowledge of performance. In Great Britain,

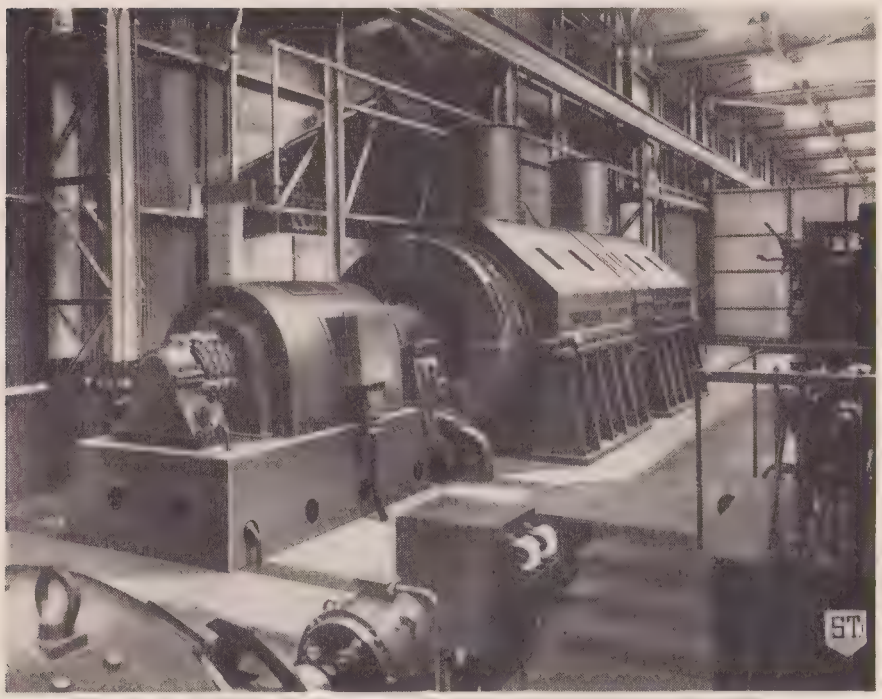


FIG. 12-2—*Typical Generator Room in Short-Circuit Test Plant (The Switchgear Testing Co., Ltd.).*

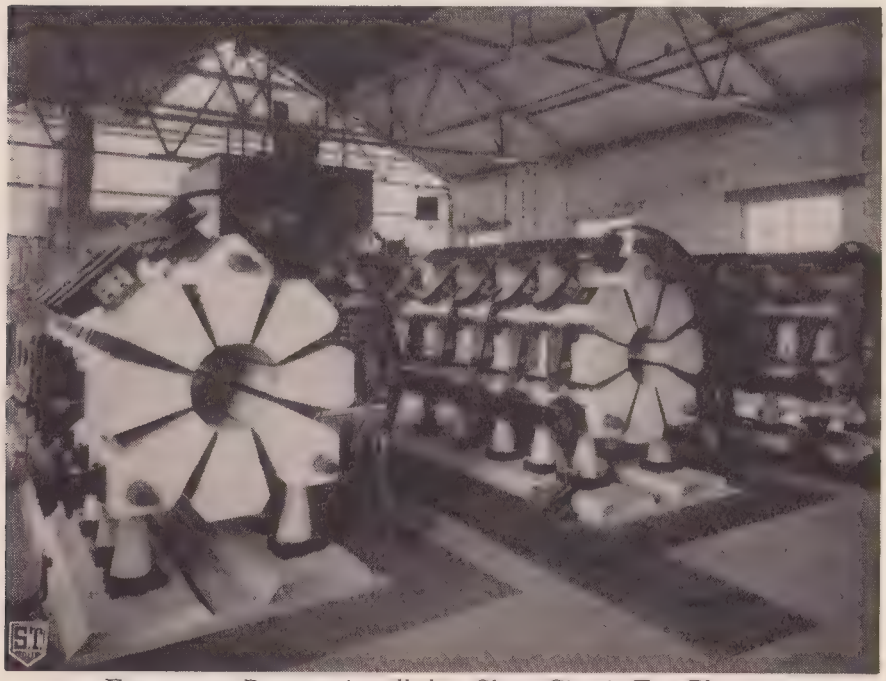


FIG. 12-3—*Reactors installed at Short-Circuit Test Plant (The Switchgear Testing Co., Ltd.).*

there are five test plants, all belonging to manufacturers. They are associated in the interests of standardisation under the title "The Association of Short-Circuit Testing Authorities" and issue certificates of rating which are accepted the world over as sufficient evidence of ability. A typical certificate is shown in Fig. 12-1. Similar test plants exist in America and on the Continent of Europe.

In this chapter, the typical equipment and features of a test plant will be outlined; then will follow an outline of the conditions and regulations for short-circuit testing as laid down in British Standard Specifications 116 and 936, and finally, a short description of the methods of evaluating electromagnetic oscillograms such as are issued by the Authority, together with details of an actual set of tests.

Typical Test Plant.

It is a first essential of the plant that it should be capable of reproducing all possible service conditions under the closest control and with full provision for the taking of exact and precise records of tests. In consequence, the equipment is costly and much of it will be specially designed. A highly trained staff of experts is an essential to the running of the plant and to assessing the performance of apparatus on test.

Generator Room.

The main item of equipment is the generator which must be capable of giving an initial short-circuit output up to 2,000 MVA symmetrical and 2,500 MVA asymmetrical at voltages varying over a range of about 7,300-12,700 volts. Arrangements exist to couple the phases in star or delta. Intermediate voltages are obtained by field regulation. In some respects, the generator resembles an ordinary large power station machine, but its electrical design has to be such that it will deliver, for a short period, an output equivalent to several times that of the largest power station and yet its mechanical construction must be such as to enable it to withstand the great stresses due to sudden and repeated short-circuits.

A typical machine weighs about 120 tons, with an 80 ton stator and a 30 ton rotor, the latter being made from a single solid steel forging with a heavy damper winding. The stator has special features to limit the reactance to a minimum. Instead of the 15-20 per cent. usually inherent in a commercial machine, a short-circuit test generator may have a reactance as low as 2·5/3·0%.

The generator is driven by a motor large enough to get the set up to full speed as quickly as possible, and to run the rotor continuously at full speed. In a typical plant, this is a 1,200 h.p. motor, running at 2,970 r.p.m. is three-phase 6,600 volt and coupled direct to the generator shaft extension. In order to relieve the supply system of heavy peak loads, the driving motor is disconnected immediately before the application of the short-circuit. Fig. 12-2 shows a typical generator room.

In order to maintain the flux in the generator and thus diminish the decrement of the short-circuit current and also to enable higher values of recovery voltage and short-circuit current to be obtained, super-excitation is essential. This is arranged to boost the excitation just prior to short-circuit. In one station, normal field current is of the order of 750 amperes. A few cycles before short-circuit, the field series resistance is cut-out, increasing the generator field current to 4,500 amperes. The super exciter is a fly-wheel set, the fly-wheel weighing some 10/15 tons in order to maintain

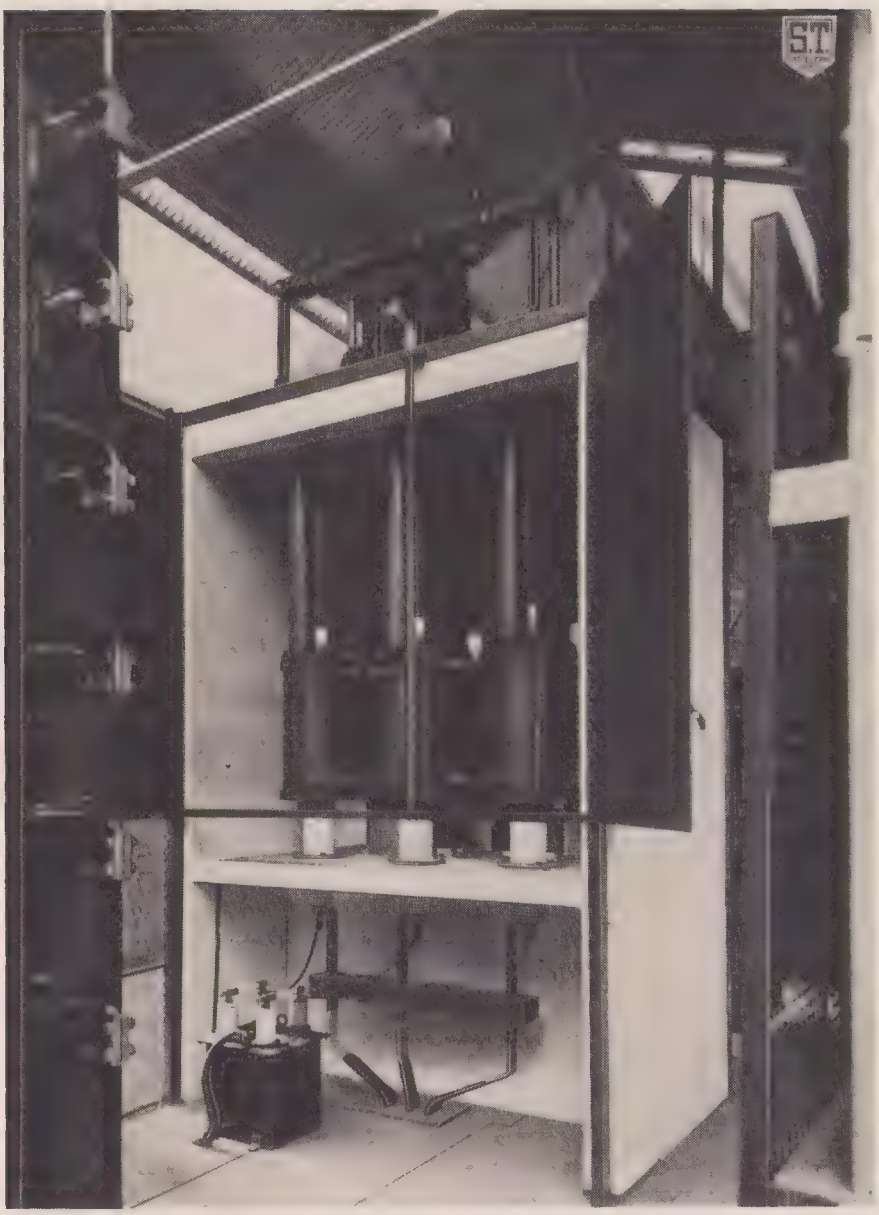


FIG. 12-4.—*Station (Master) Circuit Breaker (The Switchgear Testing Co., Ltd.).*

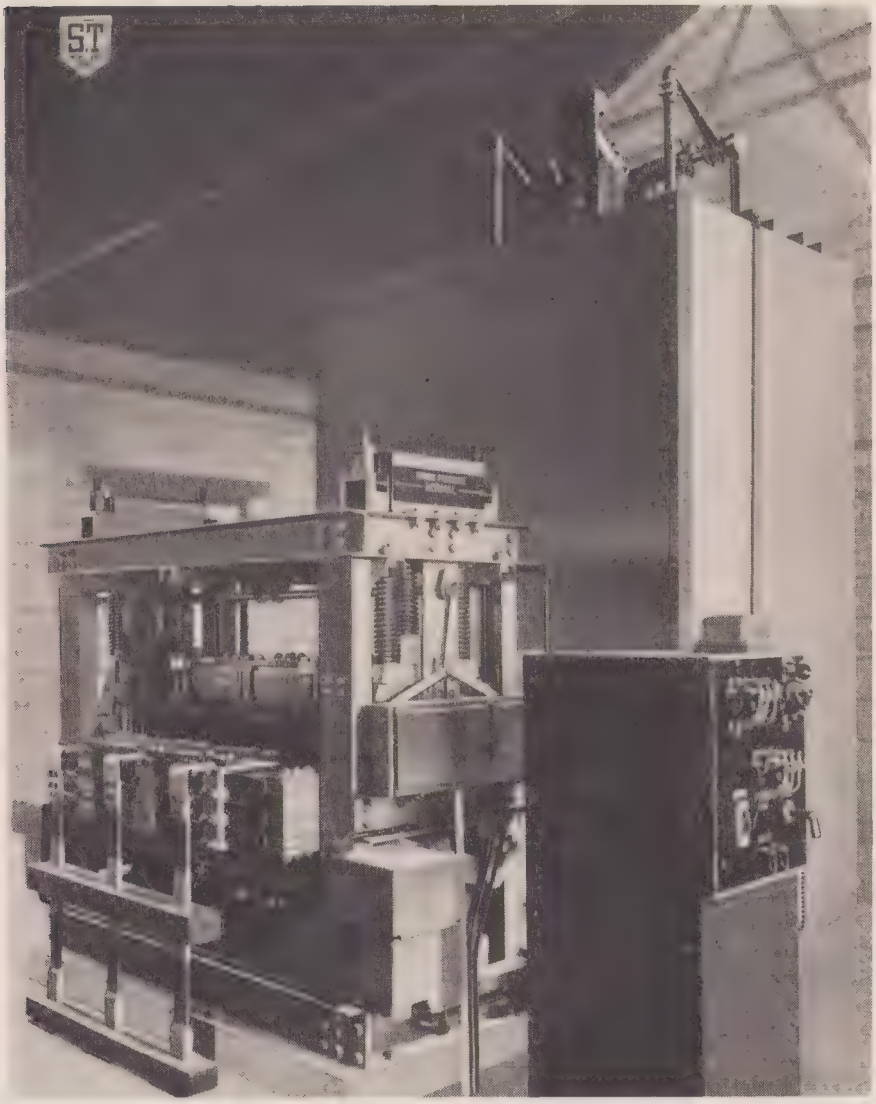


FIG. 12-5.—*Making-Switch in Short-Circuit Test Plant (The Switchgear Testing Co., Ltd.).*

speed during tests. The generator room usually houses other machines essential to the test station, such as a small motor-generator for direct-current supply to oscillograph arc lamps, an exciter set of normal proportions where super-excitation is not required, etc.

Reactor and Resistor Room.

In order to regulate the value of test current, reactors are installed, as shown in Fig. 12-3, usually of the cast-in-concrete type but specially designed to withstand the repeated stresses of short-circuit. By means of links, close grading of reactance and rapid changing of value can be obtained.

For controlling the decrement of the D.C. component of short-circuit current within a power factor range of 0·05 to 0·30 (the usual power factor for short circuit tests—see B.S.116 and B.S.936), banks of resistors are installed, suitable for heavy currents. A light current bank is available for testing under normal load conditions at power factors round about 0·8.

Station Breaker and Making-Switch.

When testing circuit interrupting devices the possible failure of the device is ever present. In such circumstances the station (or master) circuit-breaker must clear the short-circuit after a predetermined time, thus acting as a back-up breaker.

The severe duty of closing the circuit each time a circuit-breaker undergoes a " break " test falls on the making switch. This does not at any time have to break power but has to close and hold in good contact on peak currents up to 500 kA.

A high speed of closing is essential and the making-switch is usually of the air insulated type, spring closed. Up to 40/50% of the tests involve the making-switch closing to complete the short-circuit. Figs. 12-4 and 12-5 illustrate a typical station breaker and making-switch respectively.

Transformers.

For voltages above and below those available from the generator, transformers are necessary. For higher voltages, a bank of single-phase transformers is usual, and in the larger stations these give voltages up to 132 kV at present. Higher voltages may shortly be necessary.

For lower voltage testing, a three-phase transformer is installed to provide a range of voltages down to 400 volts.

Test Bays.

For testing circuit-breakers other than the largest outdoor type (usually also high voltage) covered bays are provided. Built in reinforced concrete, the front of the bay is open to provide for observation of the apparatus under test. Fire fighting apparatus is installed which can be brought into action instantly from the control room. Remote controlled fire-proof doors can be closed in the event of trouble. Fig. 12-6 shows a typical arrangement. Fig. 12-7 shows outdoor high-voltage circuit-breakers set up for tests.

Control House.

Remote from the generator room and test bays, a control house provides for the housing of all control and recording apparatus, together with rooms for the observation of the tests. Observation is through armour-plate windows, proof against explosion in a test bay.

FIG. 12-6.—*Typical Test Cells (The Switchgear Testing Co., Ltd.).*

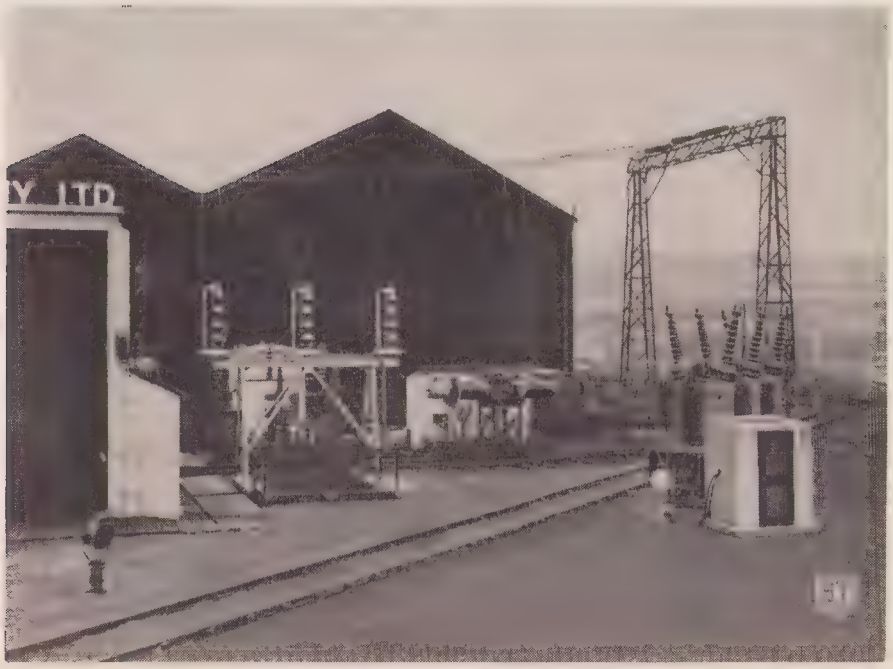


FIG. 12-7.—*High-voltage Circuit-Breakers set up for test (The Switchgear Testing Co., Ltd.).*

The recording apparatus will include an electromagnetic oscillograph capable of recording :—

Each of the three phase currents.
Each of the three phase voltages.
Each of the three arc powers.
Fluid pressure.
Travel curve.
Trip coil current.
Closing coil current.
Generator voltage.

Typical oscillograms are given later.

Fig. 12-8.—*Control Equipment for Short-Circuit Test Plant (The Switchgear Testing Co., Ltd.).*

For recording the high frequency transient restriking voltage which occurs at the instant of arc interruption, a high-speed cathode-ray oscillograph is installed. Fig. 12-8 is typical of a control room, showing the main control desk (left), the cathode-ray oscillograph (far end) and the electromagnetic oscillograph (right).

Basis for S.C. Tests.

To be of value, the proving of any circuit interrupting device must be carried out under conditions previously agreed and accepted as standard. These conditions will include rules for the interpretation of results so that comparisons are on a common basis. To this end B.S. 116 and B.S. 936 are the appropriate standards for testing in Great Britain, the former Specification (1937 Edition) following, in its entirety, the International standard (see

I.E.C. Publication No. 56), B.S. 116 (in two parts) is the Specification which covers circuit-breakers for use on systems where a very marked degree of asymmetry in the short-circuit current can occur and where the restriking conditions may be severe. B.S. 936, on the other hand, concerns circuit-breakers for less onerous duty and for use on systems not exceeding 660 volts. Specifications covering fuse tests are in course of preparation.

A circuit-breaker has three major duties to perform under short-circuit. Firstly it must be capable of opening on the occurrence of a fault and of clearing the fault. Secondly, it must be capable of being closed on to a fault, and in this case, of being latched in the fully closed position until tripped free by the action of the protective devices, or tripped free immediately as when fitted with a making current release (see Chapter XIV). Thirdly, it must be capable of carrying fault current for a short time (up to 5 sec.) while another circuit-breaker (in series) is clearing a fault.

These duties are described as :—

(1) Breaking Capacity.
(2) Making Capacity.
(3) Short-Time Capacity.

In order to prove the rating of a circuit-breaker a series of test duties are prescribed as follows.

B.S. 116.

(1) B-3′-B-3′-B at 10% of rated symmetrical breaking capacity.
(2) B-3′-B-3′-B at 30% of rated symmetrical breaking capacity.
(3) B-3′-B-3′-B at 60% of rated symmetrical breaking capacity.
(4) B-3′-MB-3′-MB at not less than 100% of rated symmetrical breaking capacity and not less than 100% of rated making capacity.
(5) B-3′-B-3′-B at not less than 100% of rated asymmetrical breaking capacity.

B.S. 936.

(1) B-3′-MB at 30% of rated symmetrical breaking capacity and making capacity.
(2) B-3′-MB at not less than 100% of rated symmetrical breaking capacity and not less than 100% of rated making capacity.

In the foregoing, " B " denotes a " breaking " operation, " MB " denotes a " making " operation followed by a " breaking " operation without intentional time delay between them, while 3′ denotes a three-minute time interval. Except where stated that the value must be " not less than," a tolerance of plus or minus 20% is allowed. It is noted that there is no asymmetrical test for B.S. 936 circuit-breakers, a reasonable omission as they are intended for use on systems where no marked degree of asymmetry can occur, *i.e.*, at remote points in an electrical network.

The need for tests at values of short-circuit below 100% has often been demonstrated by failure at reduced values although successful at full rating. This is particularly the case in arc-control circuit-breakers where the value of short-circuit current is a determining factor in the operation of the device. The critical point is acknowledged to be between 10 and 30%.

In all tests, the conditions of severity must approximate closely to those expected in service and for this reason, the recovery voltage, and power factor must be within prescribed limits. Recovery voltage, or the voltage

appearing across the open contacts at current zero, must, for circuit-breakers up to and including 500 MVA, be not less than 95% of the rated service voltage. For larger breakers it is specified that the recovery voltage shall be as near to 100 per cent. as possible, but a variation is permitted depending on the rating of the breaker and the test duty. This variation is permitted

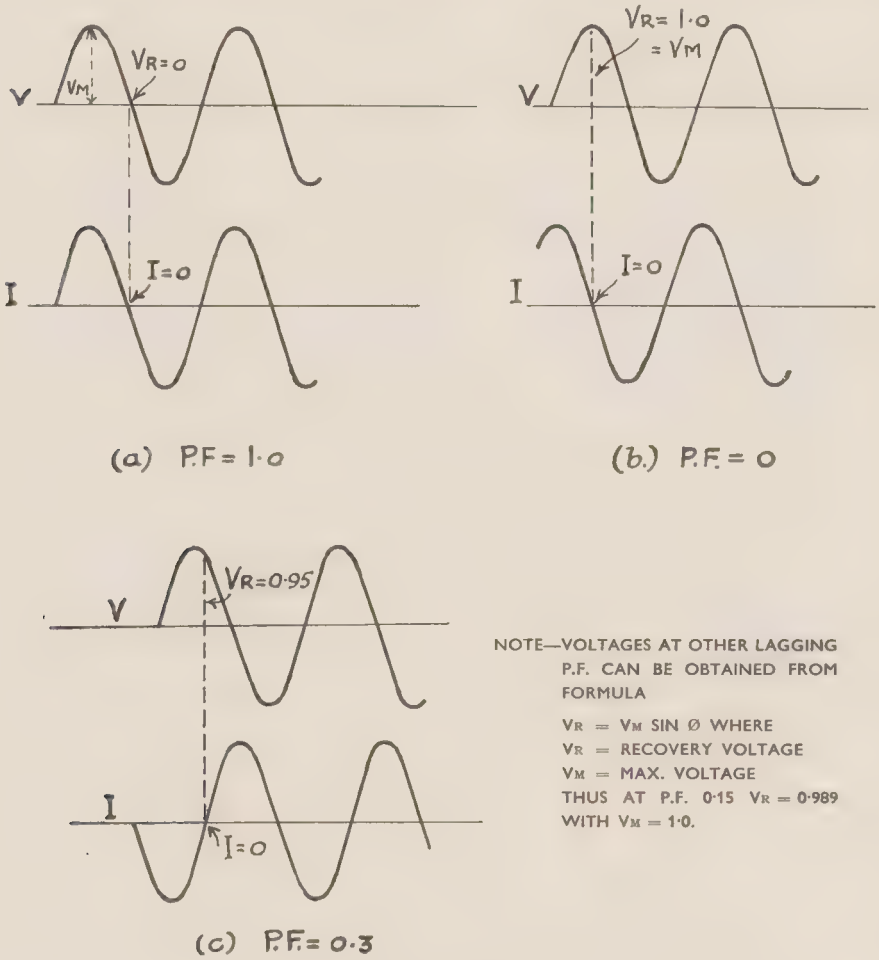


FIG. 12-9.—*Illustrating the variation of recovery voltage with power factor.*

because it is not possible, due to current decrement, to maintain high percentage values of recovery voltage at the higher values of test MVA.

Recovery voltage depends in turn on power factor and upper limits of 0·15 and 0·3 are specified. In actual tests much lower values are often obtained. How power factor affects recovery voltage is demonstrated in Fig. 12-9. Under service conditions, low power factors are to be expected at points close to the source of power, and high power factors at remote points. Harvey and Erith have produced a set of curves showing the

influence of power factor on arcing time and its effect of introducing easement in testing. They show that an increase in power factor from 0·15 to 0·3 gives approximately a 10% reduction in arcing time, and something over 10% in arc energy.

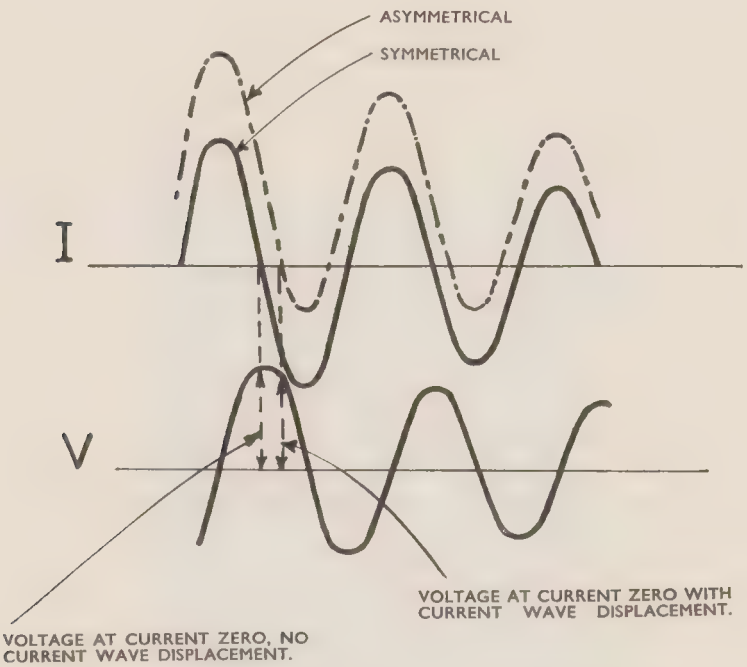


FIG. 12-10.—*Illustrating the variation of recovery voltage with current wave displacement.*

An increase from 0·15 to 0·5 gives reductions of approximately 20% and 35% respectively.

In B.S. 116, one test duty cycle must be 100% asymmetrical. No such test is specified in B.S. 936. In this asymmetrical test, the d.c. component at the instant of contact separation must be not less than 50% of the a.c. component in one phase in each " break " duty. The degree of asymmetry also affects recovery voltage, as is shown in Fig. 12-10. The degree of asymmetry to be expected on any faulted system depends largely on the ratio R/X where

R = Resistance.
X = Reactance.

In high voltage systems resistance rarely plays a large part, but in lower voltage systems, the ratio is often near to unity. The following table indicates the variation to be expected for different ratios of R/X.

R/X	Doubling Factor
Very small	1·8
0·1	1·6
0·2	1·45
0·3	1·34
0·4	1·26
0·5	1·20
0·6	1·16
0·7	1·12
0·8	1·10
0·9	1·08
1·0	1·06

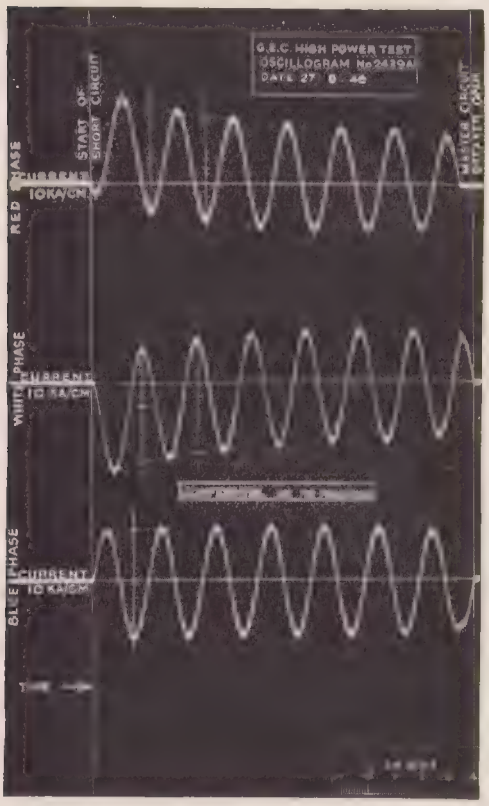


FIG. 12-11.
Typical " Circuit Calibration " or " Prospective Current " Test.

B.S. 116 includes for the highest doubling factor, *i.e.*, 1·8, while B.S. 936 accepts 1·4.

A term used in B.S. 88 (Electric Fuses) is " prospective current." This has now been introduced into oil circuit-breaker specifications. It is found that the so-called " cut-off " exhibited in a quick-acting fuse, is also exhibited in certain designs of circuit-breakers. Examples of this

are circuit-breakers with series overload (whole current) trip coils. In this case, it is necessary to determine the prospective current value of the circuit in order that the circuit-breaker may be credited with interrupting a circuit when this value can appear.

This value described as a circuit calibration test, is ascertained by replacing the circuit-breaker by a link of negligible impedance, but making no other circuit change. A typical oscillogram to determine prospective current is shown at Fig. 12-11.

The values determined from this oscillogram are :—

Peak Current in 1st major half cycle	= 88,500 amps.
Peak a.c. component	= 56,100 amps.
R.M.S. a.c. component	= 39,700 amps.
Power Factor	= 0.106.

These are the values which would be credited to a circuit-breaker tested on the same circuit but exhibiting cut-off of the short-circuit current at some lower value.

Evaluation of Electromagnetic Oscillograms.

The regular procedure of short-circuit testing of circuit-breakers means that more and more users require some evidence of such proving tests to be submitted with offers for switchgear.

It is important that oscillograms forming part of that evidence should be understood and be intelligently analysed. Students of circuit-breaker design, too, find much to be gleaned from a study of oscillograms, and this short section is, therefore, devoted to a brief description of the reading of electromagnetic oscillograms.

For this purpose reference should be made to Figs. 12-12 and 12-13, which are two specially marked oscillograms showing (Fig. 12-12) a typical 3 phase " Break " Test and (Fig. 12-13) a typical 3 phase " Make-Break " Test.

The three important points on an oscillogram are the three vertical lines drawn to indicate

Commencement of Short-Circuit	= M or CM.
Instant of Contact Separation	= CS.
Instant of Final Circuit Interruption	= B.

Of these, it will be understood that in a " break " shot, M will represent the instant at which the short-circuit is initiated by the closing of the making switch in the test station, while in a " make-break " shot, CM will represent the instant of short-circuit due to the contacts of the breaker under test making contact.

The line CS indicating contact separation shows the instant that the arcing contacts part in " breaking " and is the point at which arcing arises

The line B indicating final circuit interruption is the point at which the current is interrupted. The time between CS and B represents the " arcing time."

These three points are clearly seen in Figs. 12-12 and 12-13, and time spent on a study of these in relation to the travel curve will be worth while before considering other features of the oscillograms.

We may now consider other features and measurements as follows :—

Applied Test Voltage (Vl).

This is the line to line voltage before short-circuit and is shown in the uppermost curve and marked Vl. It is measured across the voltage wave

envelope immediately prior to the instant of short-circuit (M or CM). It is computed thus:—

$$V_L = \frac{A\ A_1}{2\sqrt{2}} *$$

MAKING CURRENT (IM).

In a "make-break" shot, the "make" test is most difficult as the breaker contacts have to close on to a peak current. The value of this peak current is that of the first *major* loop of the current wave after the instant of short-circuit CM (Fig. 12-13) and is marked IM, measured between the current zero line and the peak of the wave. It is of interest to note that in Fig. 12-13 the current wave of red phase current shows a *minor* loop immediately after CM. It will be noted, too, that the red and yellow phases show almost complete asymmetry while the blue phase is almost symmetrical.

INSTANT OF CONTACT SEPARATION (CS).

This point has been determined prior to the short-circuit tests by taking a no-load oscillograph record with direct current passing through the contacts. A break in the record indicates the instant of contact separation in relation to the travel record.

INSTANT OF CONTACT MAKE (CM).

This is determined in a similar manner to CS above, by no-load time travel records.

BREAKING CURRENT (IB).

The current broken is measured at the instant of contact separation CS.

It will be recalled that in certain duty cycles, symmetrical values of current are used, while in one duty cycle it is the asymmetrical value. The current, in the first case, is not considered to be symmetrical if the d.c. component in any phase exceeds 20 per cent. In the second case, to be asymmetrical, the current in one of the phases must have a d.c. component of 50 per cent. or more.

In Figs. 12-12 and 12-13 the d.c. component is shown by Id, and the a.c. component by Ia.

$$\text{A.C. component} = Ia = \frac{OP + ON}{2}$$

$$\text{D.C. component} = Id = \frac{OP - ON}{2}$$

$$\%\ \text{D.C. component} = \frac{Id}{Ia} \times 100$$

For Symmetrical Breaking Current, the R.M.S. symmetrical value is

$$\frac{Ia}{\sqrt{2}}$$

For Asymmetrical Breaking Current, the R.M.S. asymmetrical value is

$$\sqrt{\left(\frac{Ia}{\sqrt{2}}\right)^2 + Id^2}$$

RECOVERY VOLTAGE (VR).

The recovery voltage is measured between lines during the second

**The amplitude AA1 is shown on top wave trace Fig. 12-13.*

complete half-cycle after final circuit interruption B. This is shown at R R_1 in Fig. 12-13 and

$$Vr = \frac{R\,R_1}{2\sqrt{2}}$$

Alternatively the line-to-line recovery voltage may be derived from the average value of the phase components (Vpr) measured in each phase during the second complete half-cycle after B.

$$Vr = 3 \times Vpr \text{ (average) for a three-phase test.}$$

$$Vpr = \frac{r\,r_1}{2\sqrt{2}}$$

MVA Interrupted.

The British Standard Specifications appropriate to circuit-breakers recognise breaking capacity ratings in terms of breaking current at a rated voltage. For commercial reasons, performances may be evaluated in MVA, when

MVA interrupted = $\sqrt{3} \times$ line-to-line recovery voltage in kV $\times$ average breaking current in kilo-amps. for a three-phase test,
or
= recovery voltage in kV $\times$ breaking current in kilo-amps., for a single-phase test.

Duration of Arcing.

This is measured from the instant of contact separation CS to the instant of final circuit interrupition B. The records will give the value in terms of half-cycles* for each phase, and also in terms of arc length per break in inches, the latter being determined in conjunction with the travel record. Arc duration and arc length are clearly indicated in Fig. 12-12.

Arc Energy.

The energy dissipated in the breaker is given by the area contained under the curve of kilo-watts and is stated in kW seconds.

Duration of Short-Circuit.

Measured from M or CM to B.

Pressure Record.

All oscillograms include a record of the fluid pressures in the oil tank, or in an arc control device. The fluid pressure record is noted in both Figs. 12-12 and 12-13.

Travel Record.

A travel record shows the movement of the breaker moving contacts, both closing and opening. This record is valuable for noting whether the breaker fully closes or opens, and from the record the speeds of closing and opening are determined. The breaking speed is determined at the instant of contact separation CS by measuring the contact travel during the first 0.01 second *after* the arcing contacts have separated.

The average breaking speed is evaluated over the full separation distance of the arcing contacts up to the point at which the dashpots start to function.

The making (closing) speed is determined at the instant of contact make CM by measuring the distance travelled by the contacts in 0·01 second immediately *before* the instant of making contact.

**Later practice is to quote arc duration in terms of loops.*

OPENING TIME.

This is measured from the instant at which the trip coil receives its tripping impulse T to the instant at which the contacts separate CS.

TOTAL BREAK TIME.

This is measured from T to final circuit interruption B. This is the sum of the opening time and the arcing time.

OSCILLOGRAPH CALIBRATION.

The oscillograms Figs. 12-12 and 12-13 bear no scale by which to measure values.

Oscillograph elements are calibrated for each series of tests and the scale will be marked on each record.

ARC VOLTAGE.

This is marked in Fig. 12-12 and shows the voltage across the arc between CS and B. It is a voltage which gives some indication of the arcing period, as it starts at CS, but it must not be regarded as an infallible method of determining point CS as it is indefinite in certain cases, e.g., voltage may be indicated due to contact chatter *before* CS.

TRIP COIL AND CLOSING COIL CURRENTS.

In Figs. 12-12 and 12-13 the tripping impulse is indicated by the curve of trip coil current. It will be noted in both cases, a pause occurs at a point just before reaching a maximum. This pause indicates the resistance to the trip plunger when it meets the pole piece.

In Fig. 12-13, a curve is shown representing the current taken by the closing coil of the solenoid.

TIME VALUES.

These are obtained by reference to the 50 cycle timing wave across the bottom of the oscillogram.

MEASUREMENT OF POWER FACTOR (see references on yellow phase current wave, Fig. 12-13).

Since asymmetry occurs on at least two phases of a three-phase short-circuit, the angle θ may be determined from the curve of the D.C. component of the asymmetrical current wave between the incidence of short-circuit and the instant of contact separation as follows :—

(i) Determine the time-constant $\frac{L}{R}$ of the D.C. component, which has the general form of

$$i_d = I_{do} e^{-\frac{Rt}{L}}$$

where i_d is the value of the D.C. component at any instant.

I_{do} is the initial value of the D.C. component.

$\frac{L}{R}$ is the time-constant in seconds of the test circuit.

t is the time-interval in seconds between i_d and I_{do}.

e is the base of Napierian logarithms.

This can be readily done as follows :—

(*a*) Measure the value of I_{do} at the instant of short-circuit and the value of i_d at any other time t before contact separation.

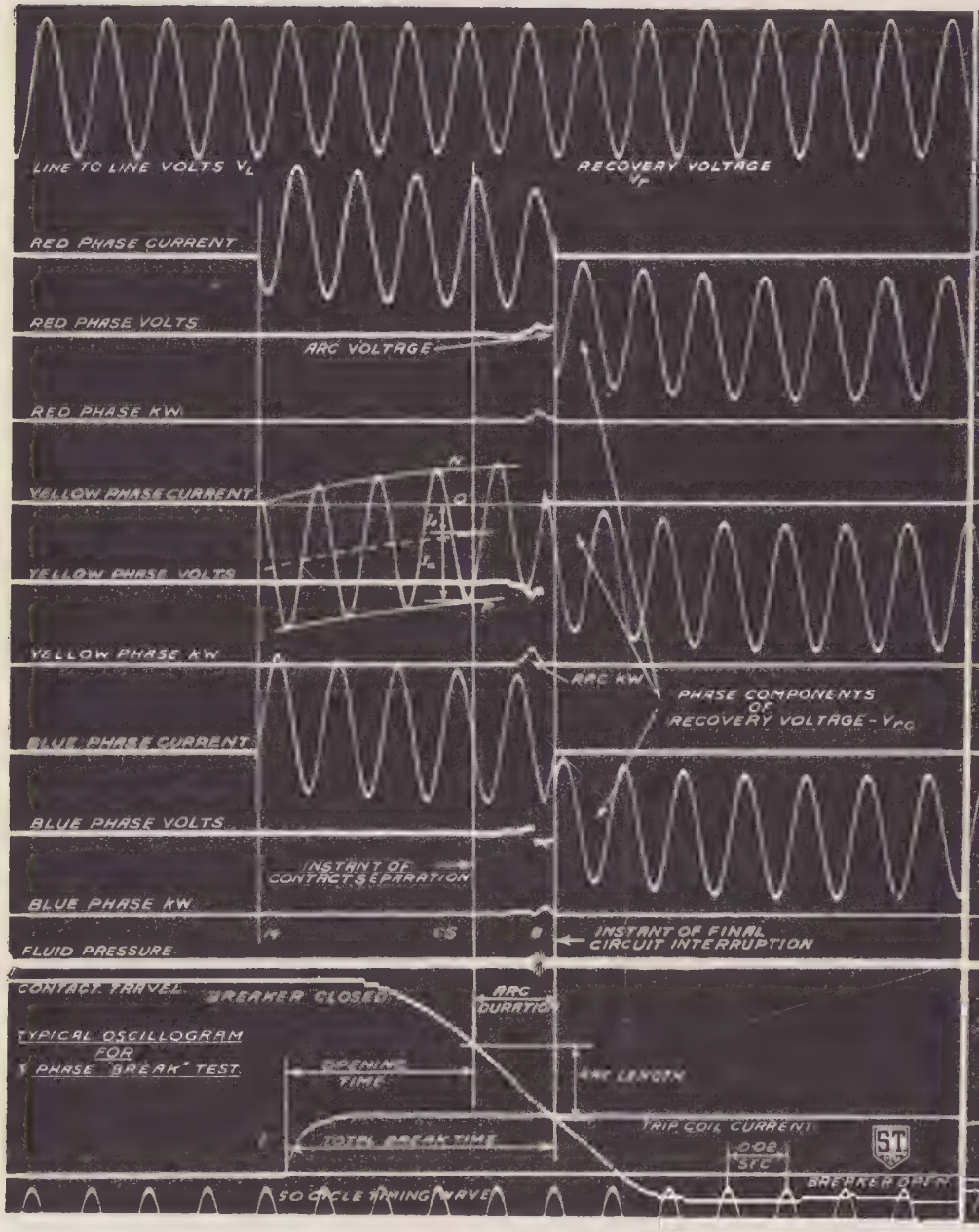


FIG. 12-12.—*Oscillograph Record of "Break" Shot.*

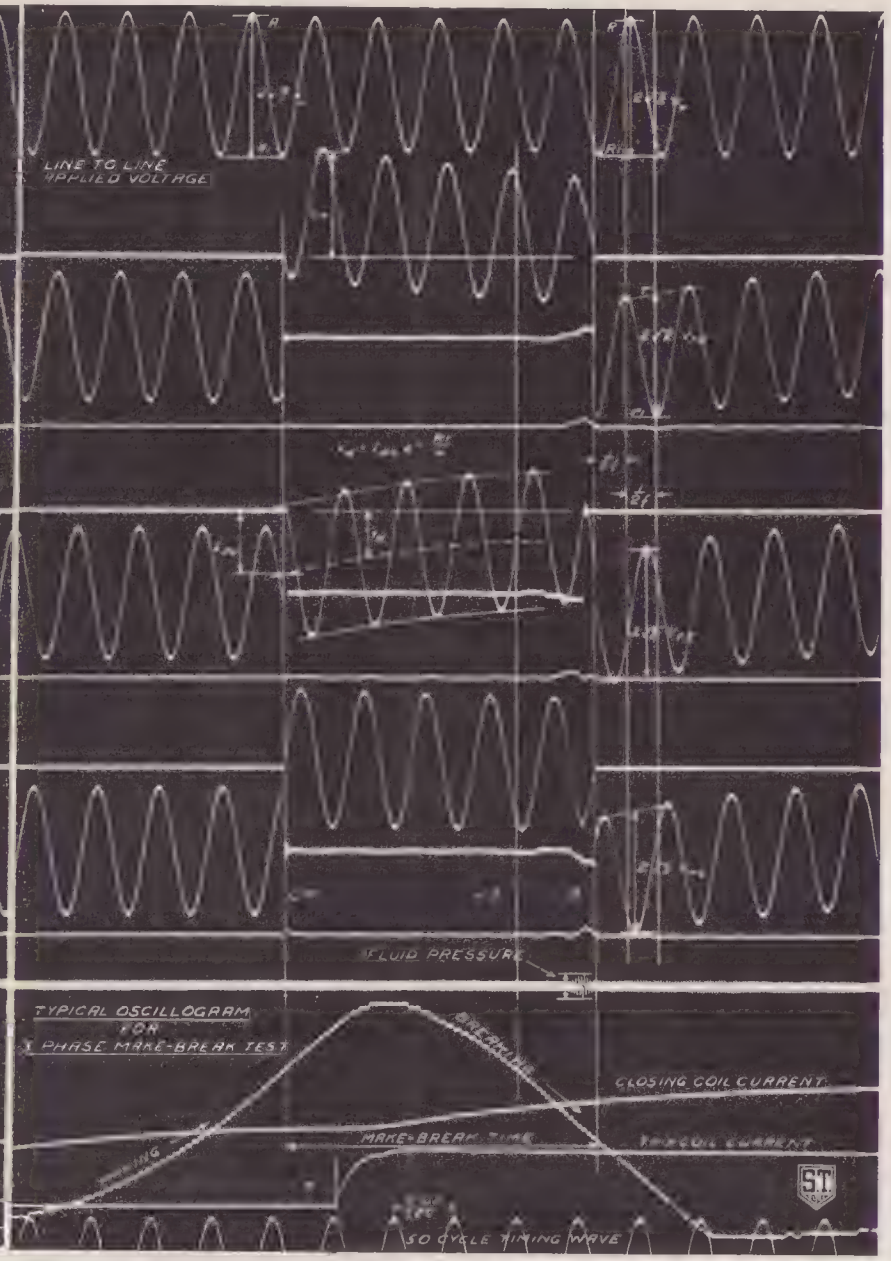


FIG. 12-13.—*Oscillograph Record of "Make-Break" Shot.*

(Reproduced by courtesy of the The Switchgear Testing Co. Ltd.)

(*b*) Determine value $e - \frac{Rt}{L}$ by dividing i_d by I_{do}.

(*c*) From a table of e^{-x} determine the value of $^{-x}$ corresponding to the ratio $\frac{i_d}{I_{do}}$.

(The value e^{-x} can be obtained readily from a Table of Napierian logarithms by taking the reciprocal of the number of which x is the logarithm.)

(*d*) The value x represents $\frac{Rt}{L}$ from which $\frac{R}{L}$ can be determined by dividing x by t, and consequently $\frac{L}{R}$ is obtained.

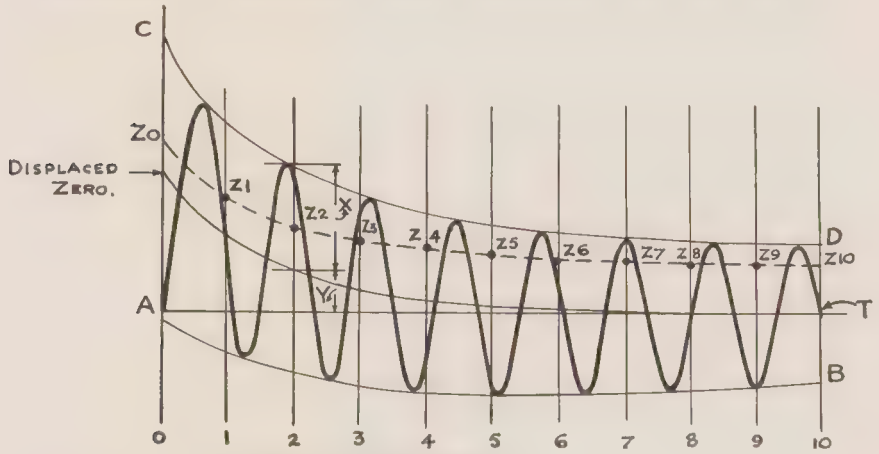
(ii) Determine the angle θ from

$$\theta = \text{arc tan } \frac{(w\ L)}{R}$$

where w is the actual frequency multiplied by 2π.

MEASUREMENT OF SHORT-TIME CURRENT.

Measurement of short-time current is illustrated in the curve, Fig. 12-14.



AT = DURATION OF SHORT CIRCUIT.
AB, CD = ENVELOPE OF CURRENT WAVE.
Z0 Z1 Z2 ETC. = RMS VALUE OF ASYMMETRICAL CURRENT AT INSTANTS 1, 2, 3, ETC.
X = PEAK VALUE OF AC COMPONENT AT ORDINATES Z0 Z1 Z2.....
Y = DC COMPONENT AT ORDINATES Z0, Z1, Z2, ETC.....

FIG. 12-14.—*Method of determining Short-time Current.*

Here the period of short-circuit on one phase is divided into 10 equal parts. At the instant represented by each ordinate, the R.M.S. value of asymmetrical current is determined by

$$Z = \sqrt{\left(\frac{X}{\sqrt{2}}\right)^2 + Y^2}$$

thus giving a series of values Z_0—Z_{10}.

Table I.

Data for Certificate No. 551 (see Fig. 12-1).

Rated Service Voltage 6,600 volts
Rated Breaking Capacity 13·1 kA at 6·6 kV = 150 MVA. Rated Making Current = 33·4 kA.

Test Duty No.	Test No.	Operating Duty and Time Interval	Breaking Current Phase	Breaking Current Symmetrical kA	Breaking Current Asymmetrical kA	Making Current Peak kA	Recovery Voltage between phases kV	Arc Duration half cycles
1	1	B	R	1·33	1·36	—	6·80	3·7
			W	1·37	1·37			3·4
			B	1·38	1·40			3·0
		3						
	2	B	R	1·36	1·37	—	6·88	3·6
			W	1·37	1·38			3·3
			B	1·38	1·38			3·0
		3						
	3	B	R	1·36	1·36	—	6·80	4·2
			W	1·37	1·38			3·9
			B	1·36	1·37			3·5
2	4	B	R	3·87	3·87	—	6·80	3·7
			W	3·96	4·00			3·4
			B	3·84	3·84			4·1
		3						
	5	B	R	3·87	3·90	—	7·00	3·1
			W	3·89	3·92			2·8
			B	3·91	3·91			3·5
		3						
	6	B	R	3·87	3·90	—	6·93	5·7
			W	3·96	3·96			3·4
			B	3·91	3·91			6·0
3	7	B	R	6·30	6·30	—	7·44	4·9
			W	6·38	6·38			4·6
			B	6·22	6·22			4·2
		3						
	8	B	R	6·30	6·30	—	7·38	3·5
			W	6·38	6·38			5·2
			B	6·35	6·35			4·8
		3						
	9	B	R	6·30	6·30	—	7·32	3·5
			W	6·38	6·38			2·2
			B	6·22	6·22			3·9
5	10	B	R	13·5	14·8	—	6·88	2·2
			W	13·6	15·0			1·8
			B	13·6	18·5			2·5
		3						
	11	B	R	13·8	17·8	—	6·84	2·5
			W	14·1	14·6			2·1
			B	13·6	15·4			2·9
		3						
	12	B	R	13·8	13·8	—	6·88	3·2
			W	13·6	18·7			3·1
			B	13·4	18·5			2·5
4a	13	MB	R	12·9	12·9	34·4	6·60	3·9
			W	13·2	13·2	21·8		2·6
			B	12·7	12·8	35·1		4·3
		3						
	14	MB	R	12·9	13·0	36·3	6·63	3·9
			W	12·3	13·4	31·4		2·7
			B	12·8	13·0	25·0		4·3
4b	15	B	R	14·7	14·7	—	6·78	3·0
			W	15·3	15·3			2·7
			B	14·7	14·7			3·4
		3						
	16	B	R	14·9	14·9	—	6·88	3·5
			W	15·6	15·6			2·2
			B	14·7	14·7			3·8
		3						
	17	B	R	14·7	14·7	—	6·84	2·9
			W	15·3	15·3			1·7
			B	14·7	14·7			3·3

Contacts not touched up or changed throughout the tests. Test duties were in order given above.

Maximum MVA broken symmetrical = 180 MVA—Test No. 16.

The equivalent R.M.S. value of current over the period of test is given by

$$\sqrt{\tfrac{1}{30}\,[Z^2_0 + 4\,(Z^2_1 + Z^2_3 + Z^2_5 + Z^2_7 + Z^2_9) + 2\,(Z^2_2 + Z^2_4 + Z^2_6 + Z^2_8) + Z^2_{10}]}$$

Example of Typical Short-Circuit Test.

When a circuit-breaker successfully passes the series of tests according to B.S. 116 or B.S. 936, the Authority issues a Certificate of Making Capacity and Breaking Capacity Rating. A typical certificate is reproduced in Fig. 12-1 for a 6,600 volt circuit-breaker having a rating of 150 MVA. Accompanying the certificate is a full record of the series of tests, with oscillograms, test data as measured from the oscillograms, and a general report of performance. The major data given are reproduced in Table I.

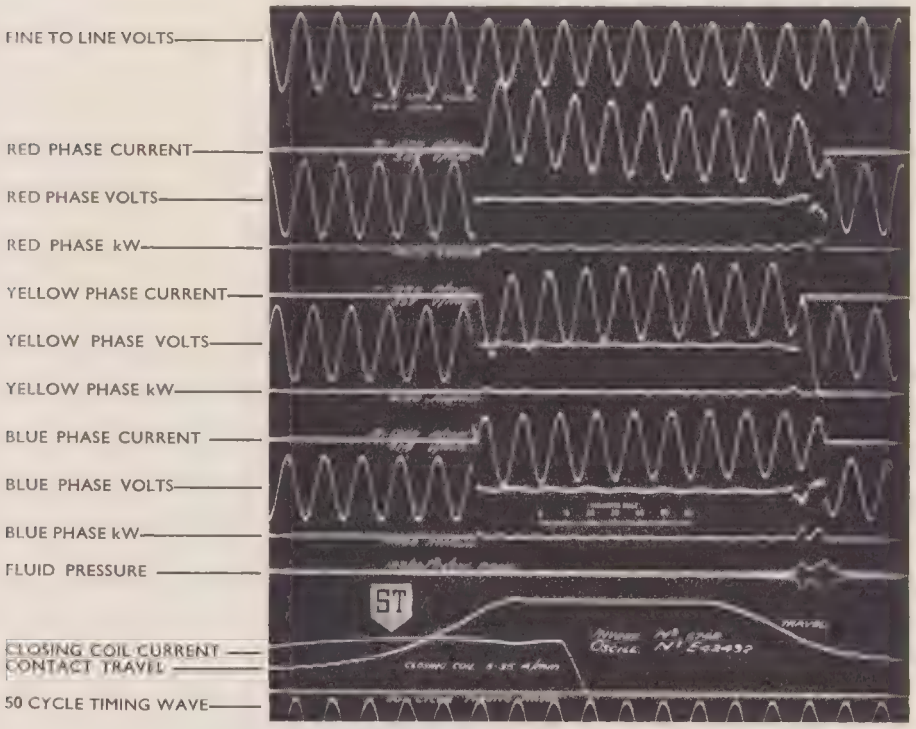


Fig. 12-15—*Oscillogram of Make-Break Test, 150 MVA at 6·6 kV (Test No. 14, Table I).*

Additional data gives details of power factor, making and breaking speeds at contact " make " and " separation," arcing times in seconds, arc energy, and fluid pressures.

A typical oscillogram is shown at Fig. 12-15, which is the oscillogram for test No. 14 in Table I.

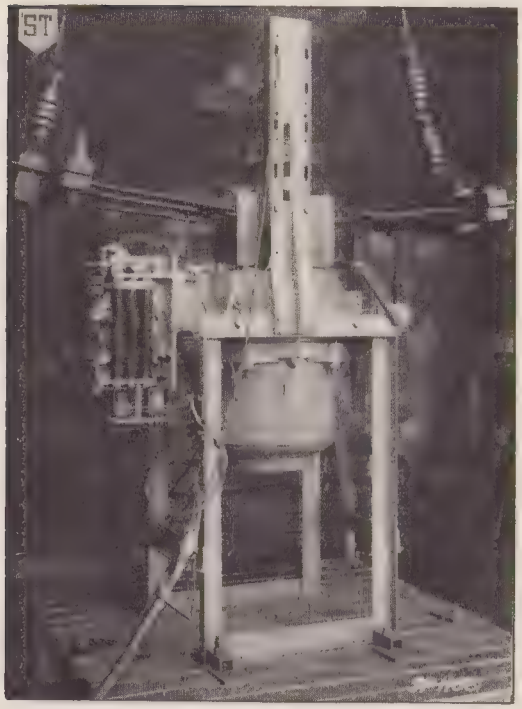


FIG. 12-16.—
Circuit-Breaker, Spring Closed, set up in Test Cell.

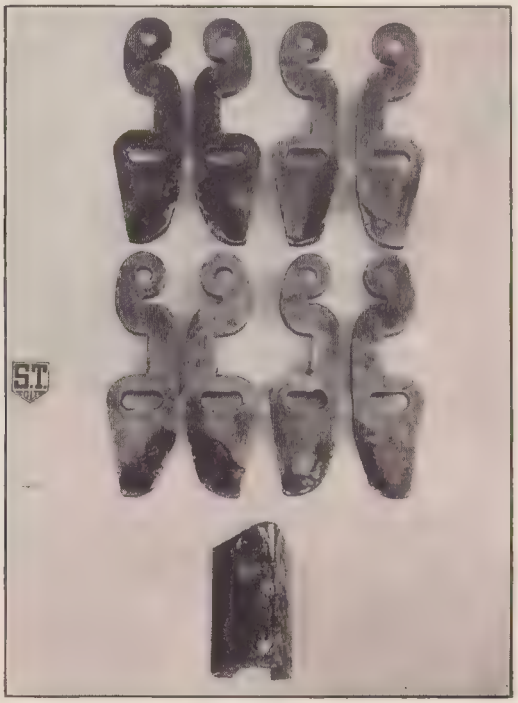


FIG. 12-17.—
Typical set of Arcing Contacts after full series of tests.

It will be noted that the test duties in Table I vary in order compared with B.S. 116. There is no compulsion to take the test duties in any order and with certain types of circuit-breaker it is usual to take a low test and a high test first, say test duties 1 and 4.

Test duty No. 4 can, under certain conditions, be divided into two tests : 4a (the making tests) and 4b (the breaking tests).

Fig. 12-16 shows a circuit-breaker set up for test in one of the test bays at a short-circuit test station, while Fig. 12-17 is a typical set of arcing contacts photographed immediately after test for inclusion in the test authority's report of performance.

BIBLIOGRAPHY.

" British Standards Specification, No. 116."

" British Standards Specification, No. 936."

" High Power Short-Circuit Testing," V. A. Brown and A. C. Ehrenberg, " The B.E.A.M.A. Journal," Vol. 41, Nos. 3, 4, 5 and 6.

" Apparatus Used for High Power Switchgear Testing," J. S. Cliff, " Journal I.E.E.," Vol. 80, No. 486, June, 1937.

" A Modern Switchgear Testing Plant," " The Metropolitan-Vickers Gazette," December, 1936.

" British Standard Specification 116-1937 and the Short-Circuit Testing of Oil Circuit-Breakers," E. E. I. Pilcher, " The Metropolitan-Vickers Gazette," December, 1937.

" Some Factors affecting the Design of Alternators for Switchgear Testing," V. Easton, " Journal I.E.E.," Vol. 90, Part II, No. 16, August, 1943.

" A New High Power Short-Circuit Testing Station," H. Astbury.

" High Power Test Plant Equipment and Methods," J. S. Cliff, " The Electrical Engineer," October 27th, 1939.

The Calculation and Design of Electrical Apparatus, W. Wilson (Chapman and Hall).

The Switchgear Handbook, Vol. I, W. A. Coates and H. Pearce (Pitman and Sons).

Calculation of Fault Currents in Electrical Networks, R. T. Lythall (Pitman and Sons).

" The Proving of Oil Circuit-Breakers under Short-Circuit Conditions," A. P. Harvey and H. A. Erith, " Journal I.E.E.," Vol. 88, Part I, No. 7.

" Short-Circuit Power-Factor," C. J. O. Garrard, " Electrical Review," May 26th, 1939.

" Some Factors Affecting the Design of Alternators for Switchgear Testing," V. Easton, " Journal I.E.E.," Vol. 90, Part II, No. 16, August, 1943.

CHAPTER XIII

SHORT-CIRCUIT CALCULATIONS

The importance of determining the values of fault current which can appear at a given point on any network is now fully appreciated. Only with such knowledge can a circuit-breaker, or other interrupting device with the proved ability to deal with the fault current, be selected, or can the switchgear designer ensure that the associated apparatus, *e.g.*, busbars, connections, current transformers, etc., will withstand the forces which arise due to the fault current during the period just prior to the interrupting device clearing the fault.

For the purpose of circuit-breaker selection, the relatively simple method of calculation based on a three-phase fault with symmetry is sufficient. On the other hand, for the purpose of determining protective relay settings, etc., it is essential that fault values of current be known for other conditions, namely line to earth, double line to earth, and line to line (single phase), or what is known as the unsymmetrical condition. The latter demands a knowledge of the theory of symmetrical components or at least, how to use symmetrical component theory in a practical way.

This chapter will, therefore, discuss the problem of short-circuit calculations under three broad headings :—

(*a*) The three-phase symmetrical fault condition.
(*b*) The unsymmetrical fault condition.
(*c*) Short-circuit stresses in busbars, connections, etc.

In order to approach the subject logically, a brief outline of the essentials required for any calculation will be given first.

The source of fault power originates in all connected generating plants and from synchronous machines normally taking power *from* the network but which may feed power *into* the network under fault conditions. The latter is important, as with large machines a drop in frequency or voltage is commonplace under fault conditions and a feed back occurs. Large induction motors have considerable flywheel effect and may act as generators in the event of reduced frequency. All such sources of power must therefore be noted and taken into account in any calculation.

The value of fault current which can flow in any network under short-circuit conditions is limited only by the impedances in that network. A prerequisite of any calculation is a knowledge of the system impedances. Impedance is that value which combines vectorially resistance and reactance. The former in many items of plant is sufficiently small in comparison with reactance as to be of no importance and it is sufficient then to deal only in terms of reactance. This is the case for generators, transformers, synchronous machines and reactors. In the case of cable or overhead line feeders, resistance may play an important part and be of such magnitude that its effect is considerable. This is particularly so in lower voltage calculations. It may be stated as a generalisation that where the reactance exceeds three times the resistance, the latter may be ignored and the resultant calculations

will not be in error by more than 5%. If the ratio is 2 to 1, and resistance is ignored, errors up to 12% may be introduced.

The accepted method of expressing the reactance of machines, transformers, and reactors is by percentage and in order to appreciate its use, the following definition is valuable.

> "A reactance of X% will have a reactive voltage drop of X% when carrying full load current corresponding to normal rating."

Thus, a transformer is stated to have a reactance of 5% and from the definition this transformer will, if short-circuited on the secondary side and with normal full load current passed through it, have a reactive voltage drop of 5% of line to neutral voltage, the applied voltage then being 5% of the normal applied voltage. This may be expressed another way, namely that with the secondary short-circuited and with *normal* voltage applied to the primary, the symmetrical short-circuit current will be twenty times the normal full load current.

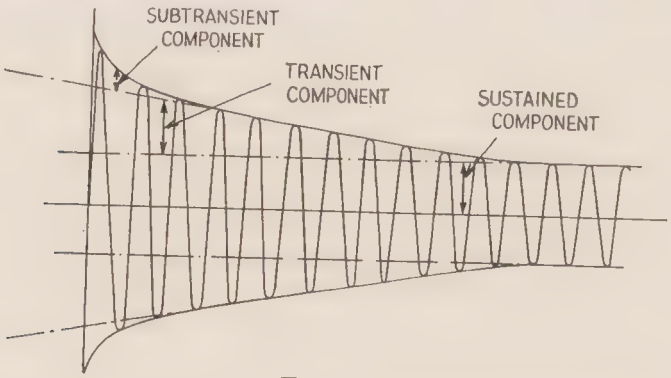


FIG. 13-1.

Some confusion may arise when considering generator reactances as there are three values, each of which has its purpose. These are described as :—

1. Subtransient reactance.
2. Transient reactance.
3. Synchronous reactance.

These in turn may be described as :—

1. A rapidly decaying component.
2. A slowly decaying component.
3. A sustained component.

They are best illustrated by the wave of symmetrical short-circuit current of a typical generator shown in Fig. 13-1.

For our purpose here we are only concerned with the subtransient value and it is this value which will be assumed in all later references.

The complication indicated above does not arise with transformers, as these are static devices. The reactance given by the manufacturer is that required for our calculations and is the sum of the leakage reactances of the high- and low-voltage windings, which, in a double wound transformer, may be represented as series reactances and can be added arithmetically. For the purpose of short-circuit calculation, no occasion arises to segregate the two.

Whereas it is general to quote machine and transformer reactances as percentages, it is usual to find cable and overhead line values given in ohms. Typical tables of values are given in the section devoted to "Useful Data," and it only remains to add that care is necessary to ascertain whether the values given in any published tables are per 1,000 yards or per mile. The ohmic values given can be readily converted to a percentage value by the use of the formula :—

$$\text{Percentage value at given kVA base for ohmic value X} = \frac{100{,}000 \times \text{kVA base} \times X}{V^2}$$

where X = value in ohms.
V = line/line voltage.

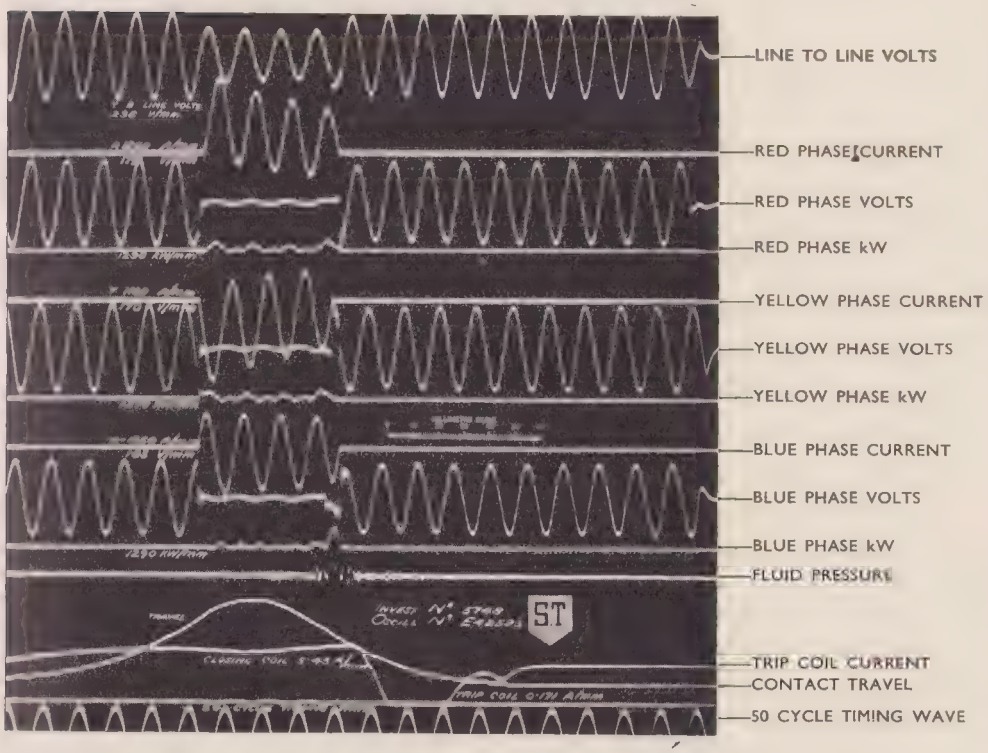


FIG. 13-2.—*Oscillogram of Make-Break Test, 75 MVA at 3·3 kV*

It may be noted that X in the foregoing may be resistance, reactance or impedance.

In the calculations of short-circuit current to be made later, the value determined will be the symmetrical value r.m.s. When a generator is short-circuited on all three phases, at least two will show a wave form which is seriously displaced about the normal zero. The extent to which this displacement (or asymmetry) occurs is dependent on the value of the phase voltage at the instant of short-circuit.

Those phases in which the voltage is at or near its maximum will have

least asymmetry, while those where the voltage is at or near its zero will have a greater or lesser degree of asymmetry. This asymmetry rapidly dies away and in a few cycles, symmetry is reached.

This is shown in Fig. 13-2, which is an oscillogram of test showing asymmetry in the red and yellow phases, and almost complete symmetry in the blue phase.

It is convenient now to summarise the essential data necessary for the calculation of fault current. Chief among these is the necessity of having available a network diagram which gives a picture of the system and showing all the sources of fault feed and all the impedances, or reactances, to the fault. On such a diagram can be indicated :—

(*a*) The size, voltage and reactance of all synchronous plant.

(*b*) The size, type, reactance, resistance and length of all interconnections, *e.g.*, cable and overhead lines, with spacings where necessary.

(*c*) The size and reactance of transformers.

(*d*) The values of any artificial reactance (reactors) introduced in the network.

Expressed more briefly, it is essential to have :—

(1) Full details of *all* plant which can *feed* into a fault.

(2) Full details of *all* factors which can *limit* the fault.

Calculations for Symmetrical Three-Phase Faults.

For all practical calculations, the percentage reactance method is one which facilitates calculation, using the reactance values given by plant manufacturer. Generators, transformers and reactors, being rated in kVA, it is also convenient to calculate in these terms and convert to values of current later, if required. For the selection of a suitable circuit-breaker it is rarely necessary to convert to current, as for commercial purposes circuit-breakers are rated in terms of kVA (or MVA) breaking capacity. It is essential, however, to relate this commercial rating to voltage, *e.g.*, 350 MVA* at 6·6 kV as this in turn determines the fault current which the circuit-breaker can deal with and it will be appreciated that 350 MVA alone may mean anything or nothing, and most certainly it cannot be assumed that a circuit-breaker rated at 350 MVA at 11kV will also be good for 350 MVA at 6·6 kV or 3·3 kV.

The plant on any network will almost always have different kVA ratings. It is a first essential in all calculations that the percentage reactances of the various plant be converted to a common base. The value of this base is unimportant and may be :—

(*a*) That of the largest machine.

(*b*) That of the total plant capacity.

(*c*) An arbitrary figure unrelated to any of the plant, *e.g.*, 100,000 kVA or 10,000 kVA.

Thus a machine or transformer having a rating of 10,000 kVA and a reactance of 10% will have a reactance of 100% on a 100,000 kVA base.

The first operation then in all short-circuit calculations by the percentage reactance method is to bring all values to the base decided upon, using the

*$MVA = \frac{kVA}{1{,}000}$ *MVA is more convenient in commercial terminology, dispensing as it does with integers.*

formula :

$$Xb\% = \frac{\text{base kVA}}{\text{plant kVA}} \times Xp\%$$

where Xb = base reactance per cent.
Xp = plant reactance per cent.

The simplest form of short-circuit calculation is that where a single generator is connected to a busbar to give supply to a number of feeder circuits. Such a system is shown in Fig. 13-3. A fault on any of the feeders (as at point F1) or on the busbars (as at point F2) will demand that either the circuit-breaker on the faulted feeder (F1) or the generator circuit-breaker for a busbar fault (F2) must open to clear the fault and the value of this will be,

$$\frac{2{,}000 \times 100}{8} = 25{,}000 \text{ kVA} = 25 \text{ MVA},$$

this being the instantaneous symmetrical value.

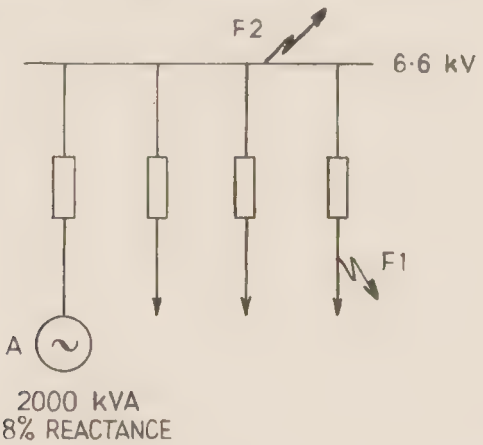


FIG. 13-3.

This example may be used to illustrate that the base kVA chosen is unimportant. It may be assumed for this purpose that instead of using the actual plant capacity, we decide on a base of 100,000 kVA. On this base, the percentage reactance will be,

$$\frac{100{,}000}{2{,}000} \times 8 = 400\%$$

and then, the fault value will be

$$\frac{100{,}000 \times 100}{400} = 25{,}000 \text{ kVA} = 25 \text{ MVA}.$$

As will be seen, as calculations take into account more complicated networks, it is convenient to reduce an electrical network as shown in Fig. 13-3 to an impedance or reactance diagram and such a diagram for the simple system would appear as in Fig. 13-4. The value of this presentation will be more obvious as we proceed.

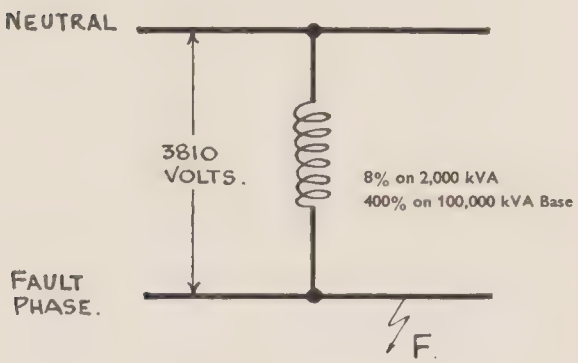
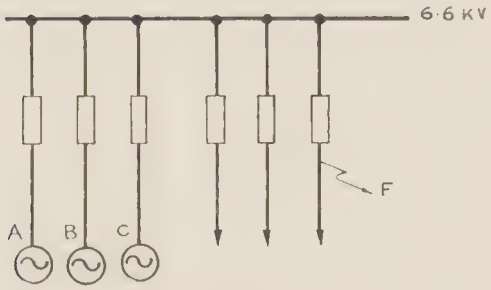


FIG. 13-4.



A = 2,000 kVA, 8% REACTANCE.
B = 5,000 kVA, 12% REACTANCE.
C = 8,000 kVA, 16% REACTANCE.

FIG. 13-5.

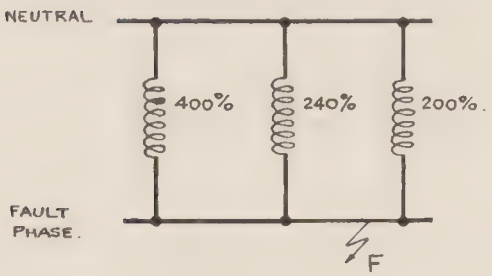


FIG. 13-6.

The system in Fig. 13-3 may now be developed by the addition of two further generators, the capacity of the three machines being different. This being the case we must decide upon a common base and bring the reactances of each machine to this base. The diagram will be as shown in Fig. 13-5 and if, for convenience, we choose a base of 100,000 kVA* we get,

$$\text{Generator A} = \frac{100{,}000 \times 8}{2{,}000} = 400\%.$$

$$\text{Generator B} = \frac{100{,}000 \times 12}{5{,}000} = 240\%.$$

$$\text{Generator C} = \frac{100{,}000 \times 16}{8{,}000} = 200\%.$$

and a reactance diagram appears as in Fig. 13-6. This shows that there are three reactances in parallel and clearly a resultant value must be obtained. This will be equal to the reciprocal of the sum of the reciprocals, thus,

$$\frac{1}{\frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3}}$$

or in the case under consideration,

$$\frac{1}{\frac{1}{400} + \frac{1}{240} + \frac{1}{200}} = \frac{1}{0{\cdot}01167}$$

$$= 85{\cdot}7\%$$

and the instantaneous symmetrical short-circuit kVA will be,

$$\frac{100{,}000 \times 100}{85{\cdot}7} = 117{,}000 \text{ kVA}$$

or 117 MVA, for which a commercially rated breaker of 150 MVA at the system voltage would be chosen.

The two examples so far calculated assume that the fault occurs on a feeder at a point close up to the station and takes no account of cable reactance or impedance.

As a next step, it may be assumed that one of the feeders is to a substation at a point one mile away and that the interconnection is by cable having a reactance of 0·125 ohms, the diagram being that shown in Fig. 13-7. The reactance of the cable being given in ohms, the first step is to convert this to a percentage base, using the formula given on page 249, thus :

$$\frac{100{,}000 \times 100{,}000 \times 0{\cdot}125}{6{,}600 \times 6{,}600} = 28{\cdot}9\%.$$

From the previous example, we know that the base kVA reactances of the machines are 400, 240 and 200% respectively and the reactance diagrams will now appear as in Fig. 13-8. This shows that there are three reactances

**This base will henceforth be used in all calculations.*

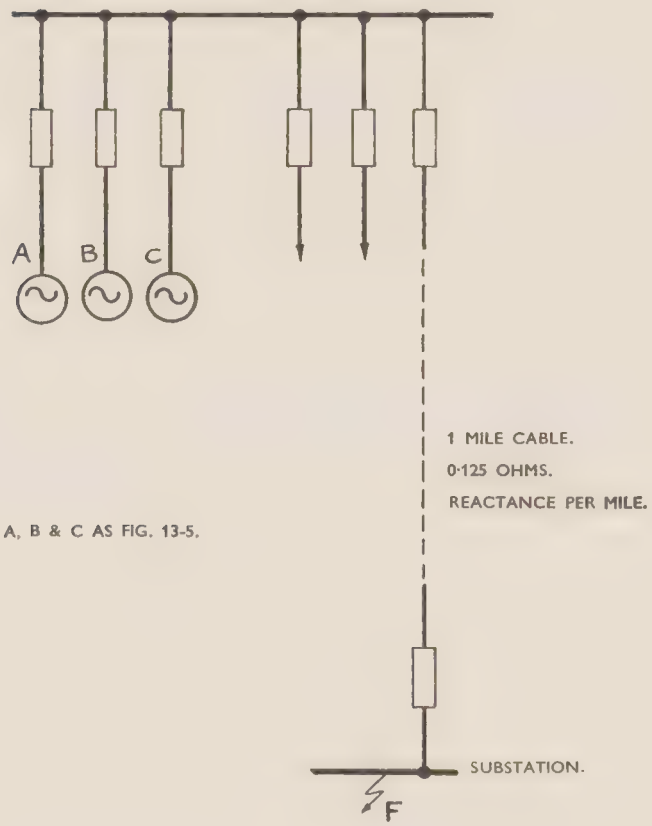


FIG. 13-7.

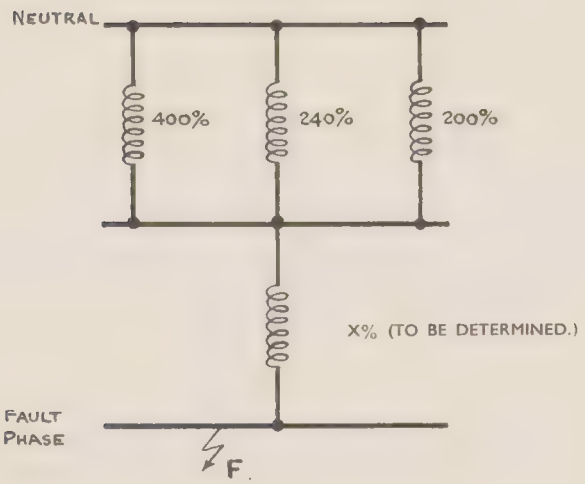


FIG. 13-8.

in parallel and that they are in series with the cable. We have already determined that the resultant of the three parallel reactances is 85·7% and therefore the reactance diagram may be reduced to that shown in Fig. 13-9 and as reactances in series are added arithmetically, this may be simplified at once to Fig. 13-10, and the instantaneous symmetrical short-circuit value is,

$$\frac{100{,}000 \times 100}{114{\cdot}6} = 87{,}200 \text{ kVA}$$
$$= 87{\cdot}2 \text{ MVA}$$

for which a standard circuit-breaker of 100 MVA at system voltage will be chosen.

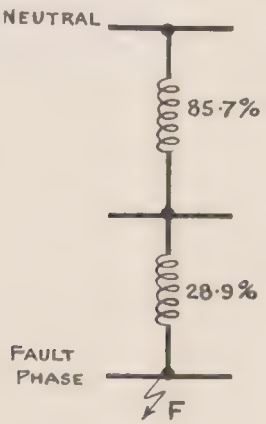


FIG. 13-9.

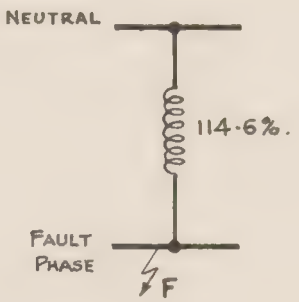


FIG. 13-10.

If, instead of one cable feeding the remote substation, there should be two cables, then account must be taken of this in the calculations. The diagram would appear as Fig. 13-11 and from our previous workings, we can show that the reactance diagram will be as shown in Fig. 13-12. The resultant value of the two cables in parallel will be 14·45% and the reactance diagram now reduces to Fig. 13-13, and the short-circuit value will be

$$\frac{100{,}000 \times 100}{100{\cdot}15} = 100{,}000 \text{ kVA (nearly)}$$
$$= 100 \text{ MVA}$$

demonstrating that the parallel feeders *increase* the fault value at the substation.

In the foregoing examples, the resistance of the cables has been ignored. A typical value of resistance might be 0·179 ohms and as this is greater than the reactance value, it is clear that its effect must be notable. To check this, let us return to the example in Fig. 13-7.

Dealing as we are in percentages, the first step is to ascertain the percentage resistance on the kVA base, again using the formula on page 249 thus :

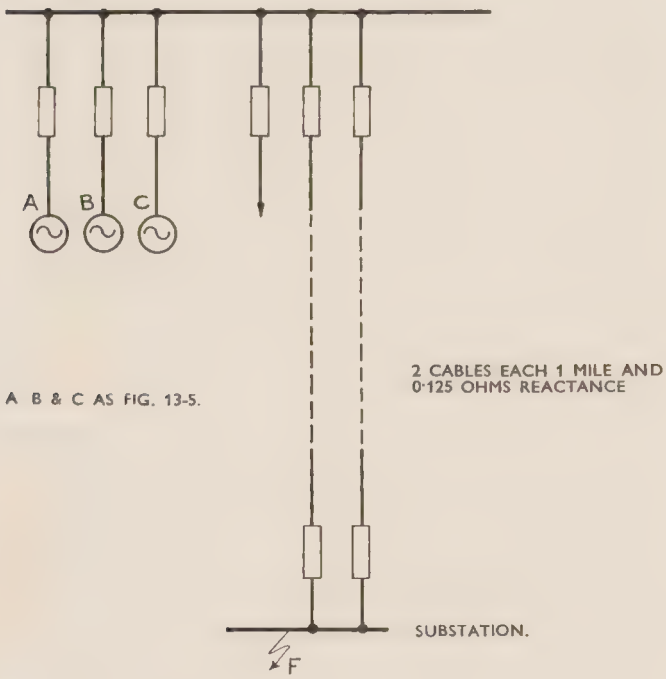


FIG. 13-11.

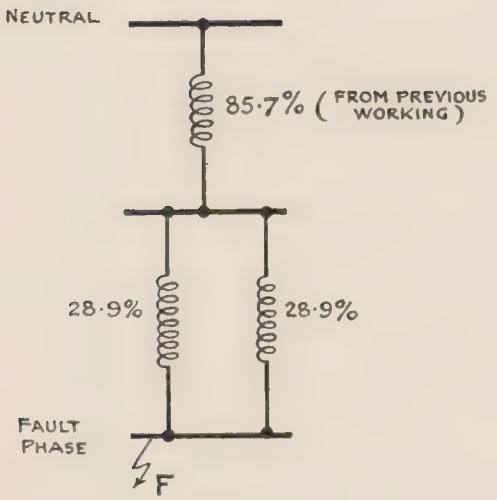


FIG. 13-12.

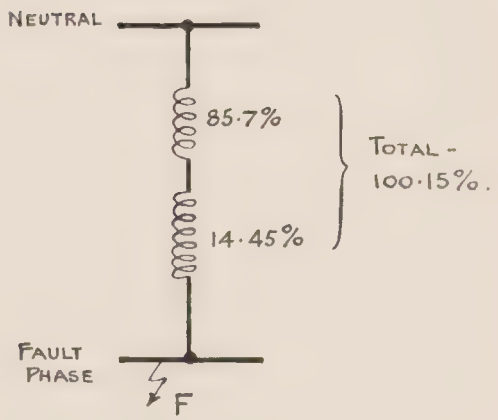


FIG. 13-13.

$$\text{Percentage resistance on kVA base} = \frac{100{,}000 \times 100{,}000 \times 0{\cdot}179}{6{,}600 \times 6{,}600}$$

$$= 41\%$$

As generator resistance may be ignored we obtain a total impedance as follows :—

$$\begin{aligned} \text{Generator} &= 0 + j\ 85{\cdot}7 \\ \text{Cable} &= 41 + j\ 28{\cdot}9 \\ \text{Total} &= 41 + j114{\cdot}6 \end{aligned}$$

$$= \sqrt{41^2 + 114{\cdot}6^2}$$

$$= 121{\cdot}7\%$$

This is the new value in place of 114·6% in Fig. 13-10 and the new short-circuit value is,

$$\frac{100{,}000 \times 100}{121{\cdot}7\%} = 82{,}000 \text{ kVA}$$

$$= 82 \text{ MVA}$$

indicating a reduction of some 5 MVA by reason of taking into account the resistance of the cable.

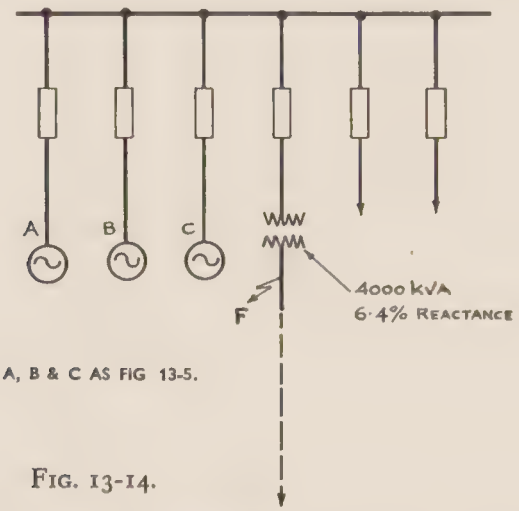


FIG. 13-14.

The introduction of transformers, whether step-up or step-down, introduces no complication into the calculation. For example, one of the feeders in the previous system might well control a 4,000 kVA transformer with a 6·4% reactance as shown in Fig. 13-14 and it is required to calculate the short-circuit value at a point just beyond the transformer, as indicated, for the purpose of selecting a circuit-breaker to install at that point. In reactance diagram form we now get Fig. 13-15 and the short circuit value is

$$\frac{100{,}000 \times 100}{245{\cdot}7} = 41{,}000 \text{ kVA}$$

$$= 41 \text{ MVA}$$

An interesting point arises out of this example. It is that where the transformer is small in relation to the plant capacity, then the generating plant need not be considered and the limiting feature is the reactance of the transformer. Generally, this can be accepted where the plant capacity is more than ten times that of the transformer, and there is no appreciable reactance between the plant and the transformer, *e.g.*, no appreciable cable run. If, for example, instead of a 4,000 kVA transformer, it had been 150 kVA with a reactance of 4·2%, then the transformer would not pass more than,

$$\frac{150 \times 100}{4{\cdot}2} = 3{,}570 \text{ kVA}$$

$$= 3{\cdot}57 \text{ MVA}$$

The example in Fig. 13-14 could be extended by ascertaining the short-circuit value at the far end of a transmission line fed by the 4,000 kVA

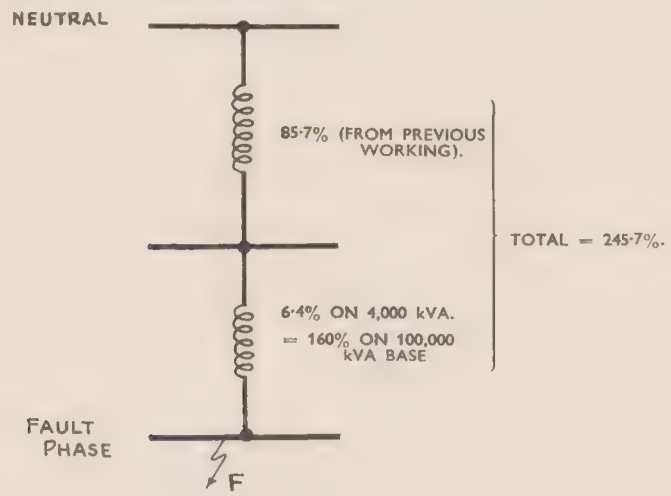


FIG. 13-15.

transformer. This problem is one which requires only the arithmetical addition of the line reactance to that of the transformer in series, the calculation proceeding as previously demonstrated.

The foregoing has demonstrated the ease with which straightforward networks may be calculated. The use of the reactance diagram is the key to all calculations as will be shown in a more complex scheme, Fig. 13-16. Here the diagram Fig. 13-5 has been used, but in this case the busbars have been divided into three sections by means of reactors.

Such a scheme would be adopted where it is essential to limit the fault kVA to some value within the ability of the circuit-breakers existing or obtainable. It is unlikely to occur in practice where the plant is of the capacity shown ; rather the case is one for much greater plant capacity but it is convenient here to retain the values with which previous examples have been calculated and thus save repetitive calculation. In order to

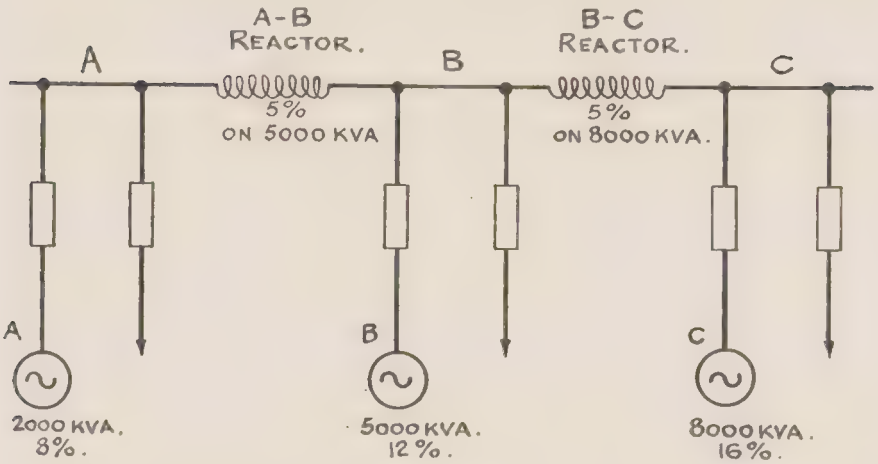


FIG. 13-16.

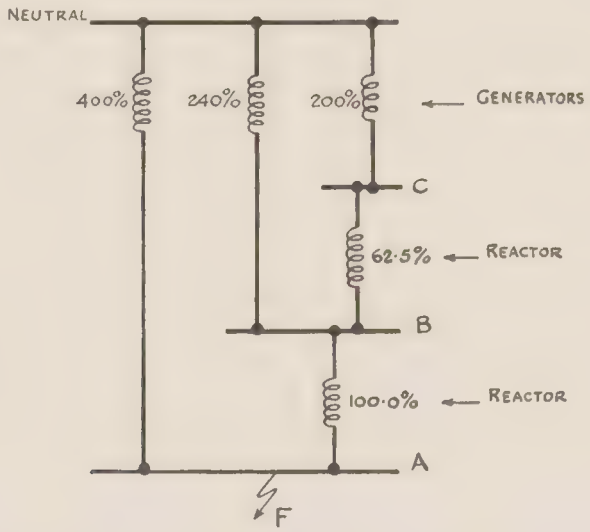


FIG. 13-17.

save reference back to the earlier example, the reactance values of the generators on the agreed base are repeated :—

Generator A = 400%
Generator B = 240%
Generator C = 200%

In this example we have the two reactors to convert, as follows :—

$$\text{Reactor A-B} = \frac{100{,}000 \times 5}{5{,}000} = 100\%$$

$$\text{Reactor B-C} = \frac{100{,}000 \times 5}{8{,}000} = 62{\cdot}5\%$$

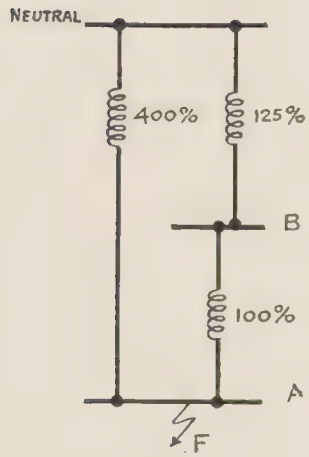


FIG. 13-18.

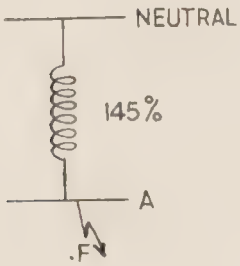


FIG. 13-19.

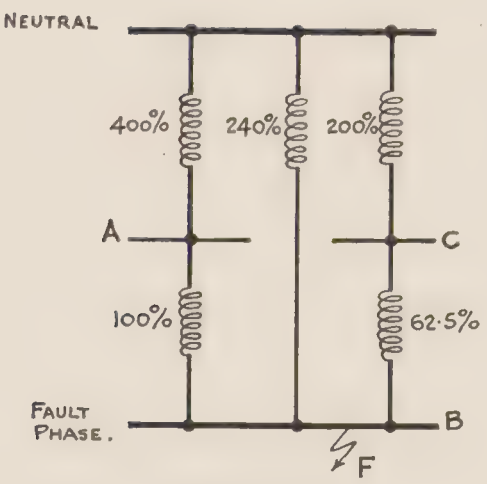


FIG. 13-20.

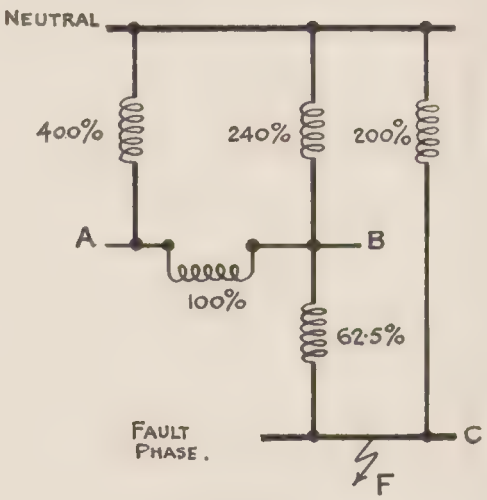


FIG. 13-21.

For a fault at busbar A, the reactance diagram would appear as shown in Fig. 13-17. A study of this diagram indicates that we must solve initially the parallel reactances 240, 200 and 62·5 to obtain a resultant value, thus :

$$\frac{1}{\frac{1}{240} + \frac{1}{200 + 62{\cdot}5}} = 125\% \text{ (approx.)}.$$

The simplified diagram now becomes that shown in Fig. 13-18, which again indicates a parallel network to be solved as follows :

$$\frac{1}{\frac{1}{400} + \frac{1}{125 + 100}} = 145\%$$

leaving a final resultant diagram as shown in Fig. 13-19 and the instantaneous symmetrical short-circuit value at busbar A is,

$$\frac{100{,}000 \times 100}{145} = 69{,}000 \text{ kVA}$$

$$= 69 \text{ MVA}$$

For a fault at busbar B, the initial reactance diagram will be that in Fig. 13-20. A study of this shows that we have a simple case of reactances in parallel, solved to give a resultant value at once by,

$$\frac{1}{\frac{1}{400+100} + \frac{1}{240} + \frac{1}{200+62{\cdot}5}} = 100\% \text{ (approx.)}$$

and therefore the short-circuit kVA at busbar B will be 100,000 kVA or 100 MVA.

For a fault at busbar C, we have a reactance diagram as shown in Fig. 13-21.

Solving first the parallel group of reactances 400, 240 and 100 we get,

$$\frac{1}{\frac{1}{400 + 100} + \frac{1}{240}} = 161\% \text{ (approx.)}$$

which leaves the reactance diagram in the form shown in Fig. 13-22 from which we determine the resultant reactance as,

$$\frac{1}{\frac{1}{161 + 62{\cdot}5} + \frac{1}{200}} = 106{\cdot}4\%$$

and the short-circuit value at busbar C is

$$\frac{100{,}000 + 100}{106{\cdot}4} = 94{,}000 \text{ kVA}$$

$$= 94 \text{ MVA}$$

The methods of reducing series and/or parallel branches of a network by step-by-step combination leading to a final single reactance has been well demonstrated in the foregoing. In examples which follow, groupings of reactances will occur connected in star or delta.

In these examples, the process of network reduction will be considerably aided by the use of two three-terminal reactance transformations, known

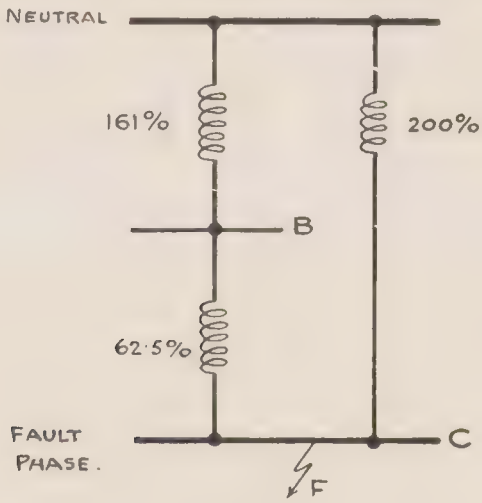


FIG. 13-22.

as the star/delta and delta/star transformations. In these any group of three vector reactances connected in star may be replaced by an equivalent

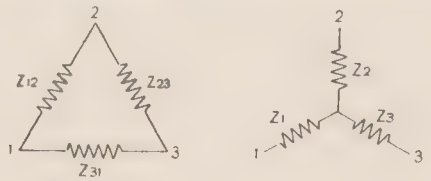


FIG. 13-23.

delta connected group, or vice-versa. For most calculations the delta/star transformation is the easiest to manipulate in reducing the network.

Thus, in Fig. 13-23, being given a delta group in which the reactances Z_{12}, Z_{23} and Z_{31} are known, the equivalent star values Z_1, Z_2 and Z_3 are :

$$Z_1 = \frac{Z_{12}\ Z_{31}}{Z_{12} + Z_{23} + Z_{31}}$$

$$Z_2 = \frac{Z_{23}\ Z_{12}}{Z_{12} + Z_{23} + Z_{31}}$$

$$Z_3 = \frac{Z_{31}\ Z_{23}}{Z_{12} + Z_{23} + Z_{31}}$$

These transformations have been determined as follows :—

$$\text{Impedance of Star} \quad 2 \text{ to } 3 = Z_2 + Z_3$$

$$\text{Admittance of Delta} \quad 2 \text{ to } 3 = \frac{1}{Z_{23}} + \frac{1}{Z_{12} + Z_{31}}$$

$$= \frac{Z_{12} + Z_{31} + Z_{23}}{Z_{23}(Z_{12} + Z_{31})}$$

$$\text{Thus Impedance of Delta} = \frac{Z_{23}(Z_{12} + Z_{31})}{Z_{12} + Z_{31} + Z_{23}}$$

and this is equal to $Z_2 + Z_3$,

$$\therefore Z_2 + Z_3 = \frac{Z_{23}(Z_{12} + Z_{31})}{Z_{12} + Z_{31} + Z_{23}}$$

$$Z_3 + Z_1 = \frac{Z_{31}(Z_{23} + Z_{12})}{Z_{12} + Z_{31} + Z_{23}}$$

$$Z_1 + Z_2 = \frac{Z_{12}(Z_{31} + Z_{23})}{Z_{12} + Z_{31} + Z_{23}}$$

from which Z_1, Z_2 and Z_3 reduce to the formula given.

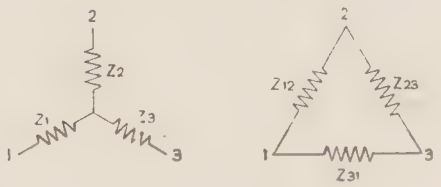


FIG. 13-24.

Given, in Fig. 13-24, the values Z_1, Z_2, Z_3, in a star connected group, the equivalent delta values are determined as follows :—

$$Z_{12} = Z_1 + Z_2 + \frac{Z_1 Z_2}{Z_3}$$

$$Z_{23} = Z_2 + Z_3 + \frac{Z_2 Z_3}{Z_1}$$

$$Z_{31} = Z_3 + Z_1 + \frac{Z_3 Z_1}{Z_2}$$

An example designed to demonstrate the use of the delta/star transformation is given in Fig. 13-25, where four generators are tied in to a ring with reactors in the busbars.

The examples Figs. 13-25 to 13-35 inclusive are reproduced from "The Calculation of Fault Currents in Electrical Networks" by permission of the Publishers, Sir Isaac Pitman and Sons, Ltd.

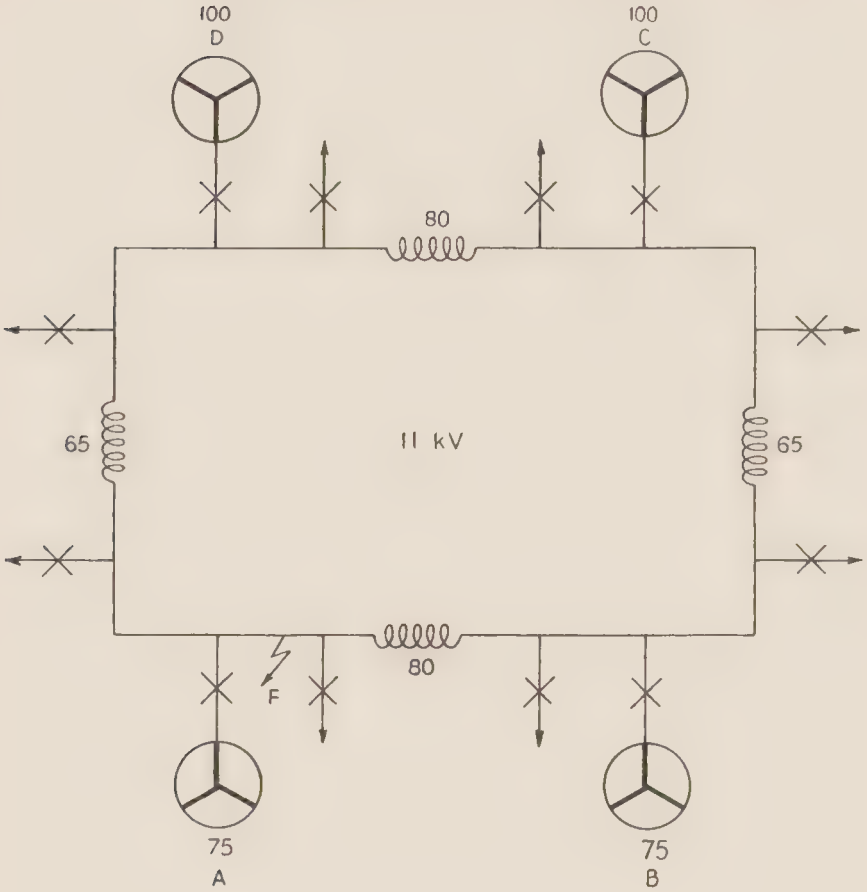


FIG. 13-25.

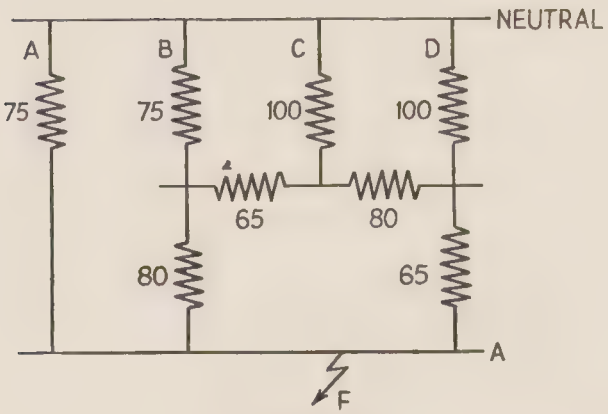


FIG. 13-26.

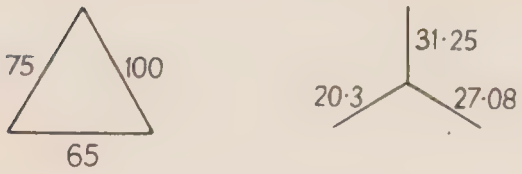


FIG. 13-27.

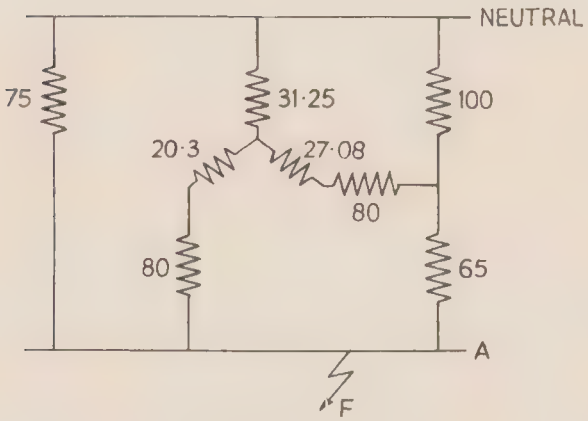


FIG. 13-28.

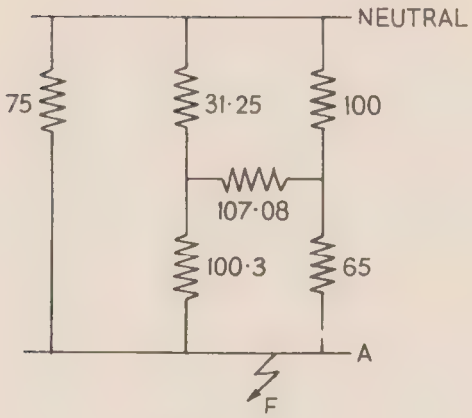


FIG. 13-29.

S

In this diagram the values of reactance are those on a 100,000 kVA base, calculated as demonstrated earlier.

For the purpose of our calculation it will be assumed that a fault occurs at the point F. The reactance diagram for this condition is shown in Fig. 13-26. A study of this diagram indicates two delta combinations, comprising the reactances :—

$$75 : 65 : 100$$
$$100 : 80 : 100$$

The simplest way of reducing the network is to convert one of these groups, introduce it into a new diagram and then convert the group which remains.

The transformation of the first group is shown in Fig. 13-27, the values in the star group having been calculated from the formula already given, thus :—

$$Z_1 = \frac{75 \times 65}{75 + 100 + 65} = 20{\cdot}3$$

$$Z_2 = \frac{100 \times 75}{75 + 100 + 65} = 31{\cdot}25$$

$$Z_3 = \frac{65 \times 100}{75 + 100 + 65} = 27{\cdot}08$$

A new network diagram may now be drawn introducing this star group and this has been done in Fig. 13-28. This diagram can be immediately simplified by adding series values, resulting in Fig. 13-29. This reveals a further delta group comprising the reactances :

$$31{\cdot}25 : 107{\cdot}08 : 100$$

Calculating as before, the equivalent star group will be as shown in Fig. 13-30 and this is introduced into the network diagram in Fig. 13-31. Adding series values again, gives Fig. 13-32. Here we find two reactances, 114·34 and 109·9, in parallel, which gives a resultant*

$$\frac{1}{\frac{1}{114{\cdot}34} + \frac{1}{109{\cdot}9}} = 56\%$$

leaving the network as shown in Fig. 13-33 which again is a parallel value problem solved by,

$$\frac{75 \times (56 + 13{\cdot}1)}{75 + (56 + 13{\cdot}1)} = 35{\cdot}96\%$$

which leaves a simple and final reactance diagram as in Fig. 13-34, from which the instantaneous symmetrical short-circuit value at F is,

$$\frac{100{,}000 \times 100}{35{\cdot}96} = 280{,}000 \text{ kVA}$$
$$= 280 \text{ MVA}$$

**Alternatively, for two values in parallel,*

$$\frac{114{\cdot}34 \times 109{\cdot}9}{114{\cdot}34 + 109{\cdot}9}$$

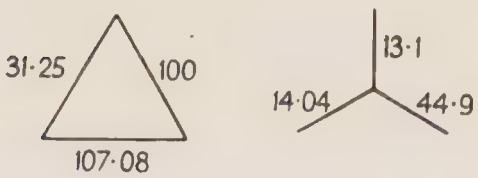


FIG. 13-30.

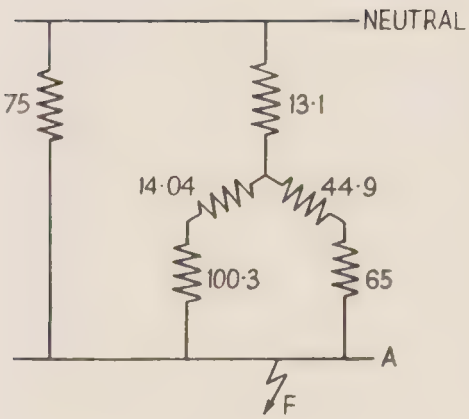


FIG. 13-31.

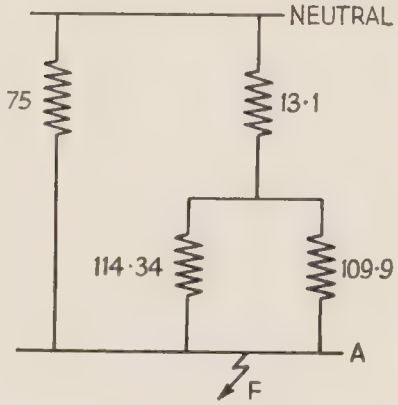


FIG. 13-32.

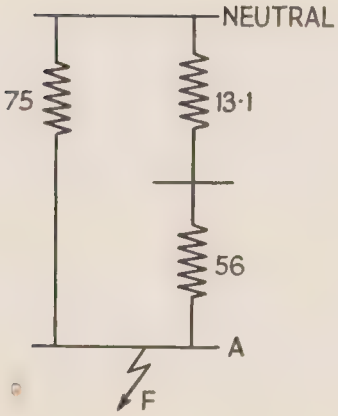


FIG. 13-33.

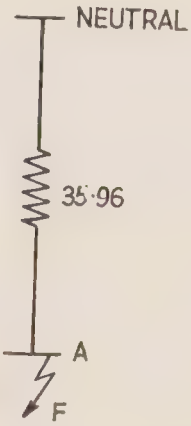


FIG. 13-34.

In order to demonstrate the opposite transformation, *i.e.*, star/delta, Fig. 13-35 has been included. This composite illustration is a good example of how network reduction is carried through. It is in a form easily followed at a glance and is similar to a diagram first devised by the author for inclusion in B.S. 936-1940.

Each of the examples calculated so far could have been worked out equally simply using ohmic values instead of percentages. When using this method, it is essential to remember that instead of using a base kVA, it is necessary to use a base voltage. When only one voltage occurs then this is naturally the base, but where, as in the case of a transmission line fed from a generating station (say at 6·6 kV) through a step-up transformer (stepping up to say 33 kV) the ohmic values must be at one or other of the voltages and conversion may be calculated from,

$$X_2 = X_1 \left(\frac{V_2}{V_1} \right)^2$$

where X_1 = ohms reactance at normal voltage.
X_2 = ohms reactance at base voltage.
V_1 = normal voltage.
V_2 = base voltage.

Given the percentage reactance of a machine or transformer, the ohmic value can be readily arrived at from,

$$\text{X ohms} = \frac{\text{X per cent.} \times 10 \times (\text{kV})^2}{\text{kVA}}$$

where kV = line/line voltage in kV

Then, if we have a 2,000 kVA generator with a reactance of 8%, the voltage being 6·6 kV, we find that

$$\text{X ohms} = \frac{8 \times 10 \times (6{\cdot}6)^2}{2{,}000} = 1{\cdot}74 \text{ ohms.}$$

Circuit reduction is made exactly as in the percentage reactance method. Having arrived at a final single reactance in ohms, the short-circuit *current* is determined from,

$$\text{Inst. Sym. S.C. Current} = \frac{V}{X}$$

where V = line to neutral volts.
X = reactance in ohms.

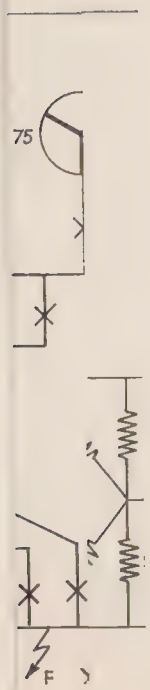
Thus, in the case of the 2,000 kVA generator in the previous example, the instantaneous symmetrical S.C. current would be,

$$\frac{3{,}810}{1{\cdot}74} = 2{,}189 \text{ amperes.}$$

and the short-circuit kVA,

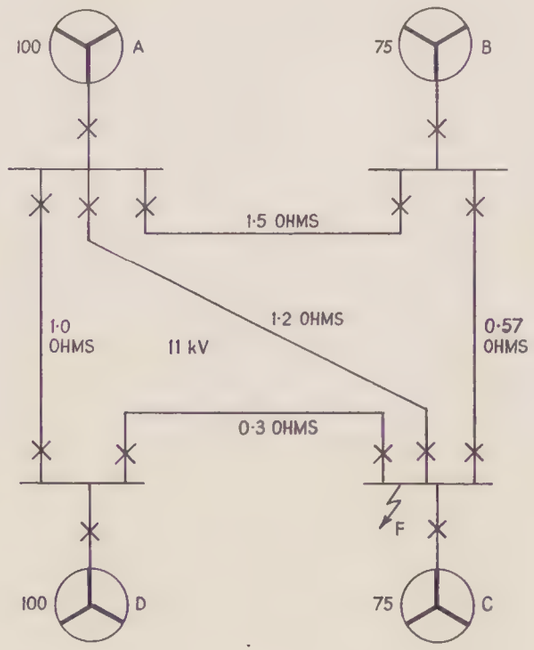
$$\frac{2{,}189 \times 3{,}810 \times 3}{1{,}000} = 25{,}000 \text{ kVA}$$

$$= 25 \text{ MVA}$$



examples.

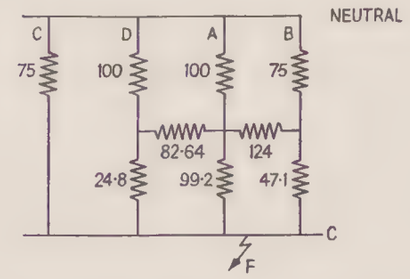
*"Calculation of Fault Currents in Electrical Networks," Pitman & Sons, Ltd.



A

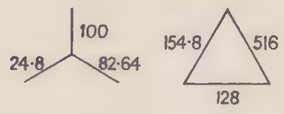
In the system shown above, four power units feed into a ring with a tie between two stations. It is desired to ascertain the fault value for a short-circuit at F. Reactance values for the generators are on a 100,000 kVA base. Ohmic values for cables must be converted to percentage values on the base kVA. These work out as follows :-

1.0 ohm = 82.64 per cent. 1.5 ohm = 124.0 per cent.
0.3 ohm = 24·8 per cent. 1.2 ohm = 99.2 per cent.
0.57 ohm = 47.1 per cent.



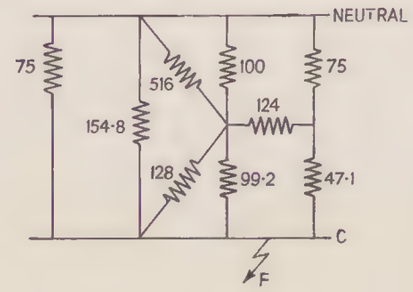
B

The system as shown at (A) may now be set out as a network diagram.



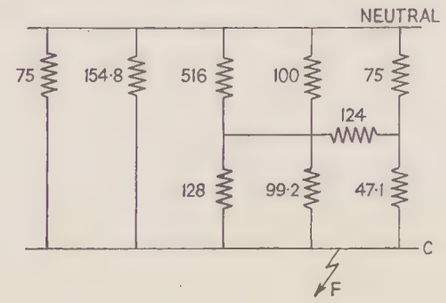
C

In the diagram (B) a star network is noted having the values 100 : 82.64 : 24.8. This is converted to a delta group as above.



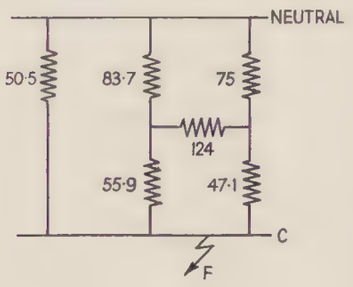
D

The delta group has been inserted in the network diagram.



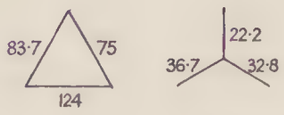
E

The diagram (D) has been simplified to show the delta group in a different form, more easily visualised for subsequent reduction.



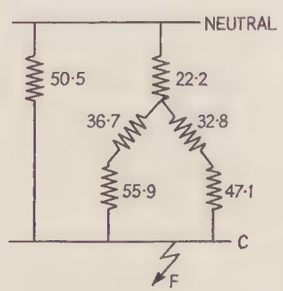
F

In (E) a number of parallel values appear and when these have been reduced, the network diagram is as above.



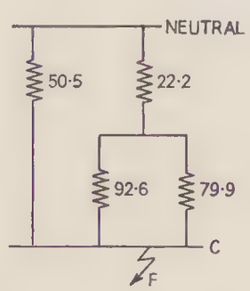
G

In (F) a delta group appears having the values 83.7 : 124 : 75. which are converted into a star group.



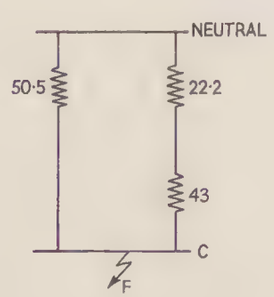
H

The star group is introduced into the network diagram.



J

Series values in (H) have been added arithmetically to give a new network diagram.



K

The parallel values 92.6 and 79.9 in (J) have been reduced to an equivalent single value.

L

The parallel values 50.5 and (22.2 + 43) have been reduced to give a final single reactance of 28.5. From this, the fault value is

$$\frac{100{,}000 \times 100}{28\,5 \times 1000} = 352 \text{ MVA}$$

FIG. 13-35.—*An example of Network Reduction to determine fault MVA for a fault at known point.*

which is the answer obtained in the example shown in Fig. 13-3 by the percentage reactance method.

The ohmic method has been worked out in greater detail elsewhere* by the author and is not repeated here.

So far, it may be assumed that the examples have been concerned with networks at generator or transmission voltage. No example has been given for say 400 volts, as in factory or domestic distribution. In general, the method of calculation is the same. For example, in Fig. 13-36, a 400 volt network is fed from a 500 kVA transformer having a reactance of 4·5%. This is a simple case and the nominal short-circuit kVA at 400 volts would be,

$$\frac{500 \times 100}{4{\cdot}5} = 11{,}100 \text{ kVA} = 11{\cdot}1 \text{ MVA}$$

a calculation which does not differ in method from that for Fig. 13-3.

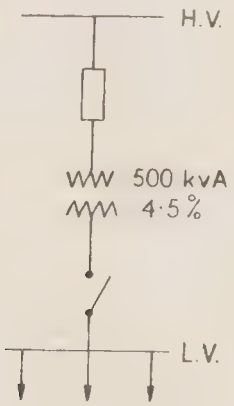


FIG. 13-36.

There are, however, two important factors which must be taken into account and which, in many systems, can have a considerable bearing on the fault values and on the type of switchgear, particularly when the fault value approaches the economic and design limit for low-voltage switchgear (see B.S. 936).

These factors are :—

(*a*) The equivalent reactance of the h.v. network which must exist to feed the l.v. network.

(*b*) The reactance, or impedance of the l.v. connections between the transformer and the switchgear.

It can be shown that these have considerable effect in reducing the short-circuit value.

Dealing first with (*a*), the effect of equivalent high-voltage reactance depends on the size of the transformer ; the smaller this is the less the influence on the low-voltage fault value. This will be clear from two examples.

*" *Calculation of Fault Currents in Electrical Networks*," Pitman & Sons, Ltd.

(1) Assume a transformer of 150 kVA having a reactance of 4%. The breaking capacity of the high-voltage switchgear controlling the transformer is 250 MVA.

Then,

Equiv. h. v. Reactance as percentage on 150 kVA base $= \frac{150 \times 100}{250 \times 1{,}000} = 0{\cdot}06\%$

The short-circuit kVA at 400 volts on Transformer reactance alone $= \frac{150 \times 100}{4} = 3{,}750$ kVA

The short-circuit kVA at 400 volts on Transformer reactance plus h.v. reactance $= \frac{150 \times 100}{(4 + 0{\cdot}06)} = 3{,}690$ kVA

showing a reduction of 1·5%.

(2) Assume a transformer of 3,000 kVA capacity having a reactance of 6% and the high-voltage switchgear again 250 MVA.

Then,

Equivalent h.v. reactance as percentage on 3,000 kVA base $= \frac{3{,}000 \times 100}{250 \times 1{,}000} = 1{\cdot}2\%$

The short-circuit kVA at 400 volts on Transformer reactance alone $= \frac{3{,}000 \times 100}{6} = 50{,}000$ kVA

The short-circuit kVA at 400 volts on Transformer reactance plus h.v. reactance $= \frac{3{,}000 \times 100}{(6 + 1{\cdot}2)} = 41{,}700$ kVA

showing a reduction of 16·5%.

From the foregoing it will be seen that the formula for determining the equivalent high-voltage reactance at the base kVA is

$$\frac{\text{Base kVA} \times 100}{\text{h.v. MVA} \times 1{,}000}$$

where h.v. MVA may be (*a*) the short-circuit rating of the h.v. switchgear, or (*b*) the known short-circuit value calculated as in the first part of this chapter. The latter value will invariably be less than the former and if known should be used. To further illustrate the importance of this factor in low-voltage calculations, Fig. 13-37 gives two curves showing (*a*) the short-circuit value based on transformer reactance alone and (*b*) based on transformer plus h.v. reactance.

The curves are drawn for transformers having reactances given in Table 3 and for a known h.v. short-circuit value of 250 MVA. Any variation in these values will modify the curves but they illustrate the point.

Dealing now with the factor of connection reactance or impedance, we recall that in the examples calculated for h.v. faults, no account was taken, for example, of the cables joining the machines to the switchgear or the switchgear to transformers.

Generally these are short and their reactance or impedance is negligible. In low-voltage layouts however, different conditions often arise and the effect of the conductor reactance or impedance is appreciable and must be

taken into account. Where the conductor is a three-core cable, no difficulty will arise in including the appropriate values for reactance or impedance as tables exist giving this information for all standard cables (see typical table in " Useful Data"). More often, however, single core cables or bare copper conductors are used because of the currents involved.

In the case of single-core cables, reference should, wherever possible, be made to the cable manufacturers for a statement of reactance or impedance for the particular run, a statement which will take account of how laid, the

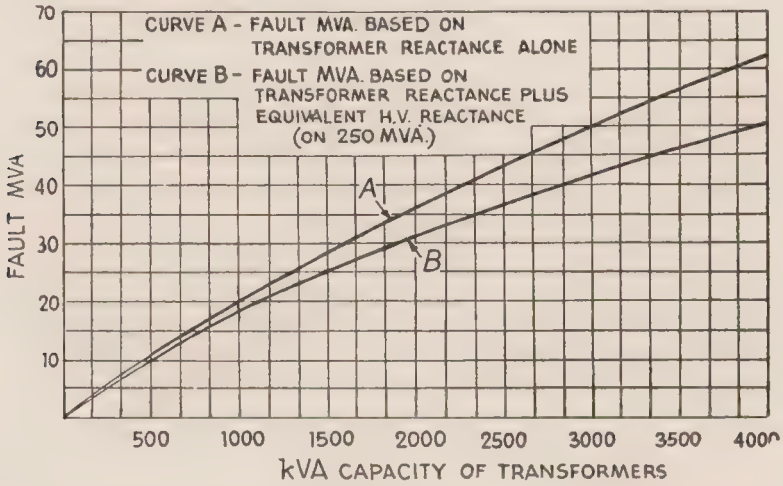


FIG. 13-37.

spacing, and the formation of the cables. In the absence of such a statement, an approximation can be obtained from the following:

$$X = 2\pi f L \times 10^{-3} \text{ ohms per 1,000 yards}$$

where X = reactance in ohms/1,000 yards
f = frequency
$L = k + 0{\cdot}421 \log_{10} (d/r)$
k = 0·054 for 7-strand cables
0·0506 for 19-strand cables
0·0457 for 37-strand cables
d = centres (between cables) in inches
r = radius of conductor in inches

Bare conductors, on the other hand, present a separate problem as little published data is available which gives in a ready form the reactance or impedance values for the large variety of sections, spacings, etc., which are possible. To obtain these values recourse must be made to somewhat laborious arithmetic based on fundamental formulæ for self- and mutual inductance.

In an article by Trencham and Mortlock (see Bibliography) a number of curves have been produced which, when used as indicated in the article, give what is termed a " reduction factor " for a number of defined copper sections on defined spacings. The variety of arrangements is almost endless, and the curves given can only be for a selection of these variations. It will be of interest, therefore, to indicate the method by which calculation can be made

for any particular layout, obtaining results sufficiently close for the selection of suitably rated circuit-breakers. As already indicated, self- and mutual inductance enter into the calculation. In any three-phase system, the total inductance of any one phase must include the self-inductance of that phase, and the mutual inductance of that phase with each of the other two phases, the values being combined vectorially. Certain simplifications will be allowed in order to reduce the amount of arithmetic involved. These simplifications are :

(*a*) A phase conductor of multiple strips (*e.g.*, 4-4 inch $\times \frac{1}{4}$ inch) is assumed to be a consolidated single conductor equal to the dimensions of the multiple arrangement. In the above case this would be 4 inch $\times 1\frac{3}{4}$ inch, assuming that the strips are spaced $\frac{1}{4}$ inch.

(*b*) Uniform current distribution is assumed over the cross-section.

(*c*) Average values per phase are used.

For the purpose of the present chapter it will be assumed that the phases are on a horizontal plane. The essential formulæ are :—

$$\text{Self Inductance (L)} = 2S\left(\text{Log}\epsilon\frac{2S}{R} - 1 + \frac{R}{S}\right)$$

$$\text{Mutual Inductance (M)} = 2S\left(\text{Log}\epsilon\frac{2S}{d'} - 1 + \frac{d'}{S}\right)$$

where S = Length of Conductors in centimetres.

R = Geometrical Mean Distance of rectangular section on itself, cms.

d′ = Geometrical Mean Distance between rectangular sections, cms.

All logarithms are to the base ϵ, while inductances are in centimetre terms, or, more strictly, in centimetre flux lines which, when multiplied by 10^{-9} give values in henrys.

R is obtained from

$$R = 0{\cdot}2235\,(a + b)\text{ cm.}$$

where a = height of rectangular section in cms.

b = width of rectangular section in cms.

as in Fig. 13-38 (*a*).

To obtain d′, the curves in Fig. 13-38 (*b*) are used. These are based on Formula 132, Bulletin 169 of the American Bureau of Standards. Here, values of the ratio d′/d are given for various ratios d/a where

d = phase centres in centimetres.

a = height of rectangular section in centimetres.

and, as will be shown in the example, for any given value d/a, the value of d′ can be deduced from the appropriate value d′/d.

In order to demonstrate the calculations necessary to determine the reactance due to a run of bare copper connections, it will be assumed that a 1,500 kVA 50 cycle transformer, having a reactance of 5·6% is connected on its low voltage side (400 v.) to the switchgear by means of bare copper conductors consisting of three 4 inch $\times \frac{1}{4}$ inch straps per phase, spaced 5 inches apart (centres) throughout a run of 75 feet.

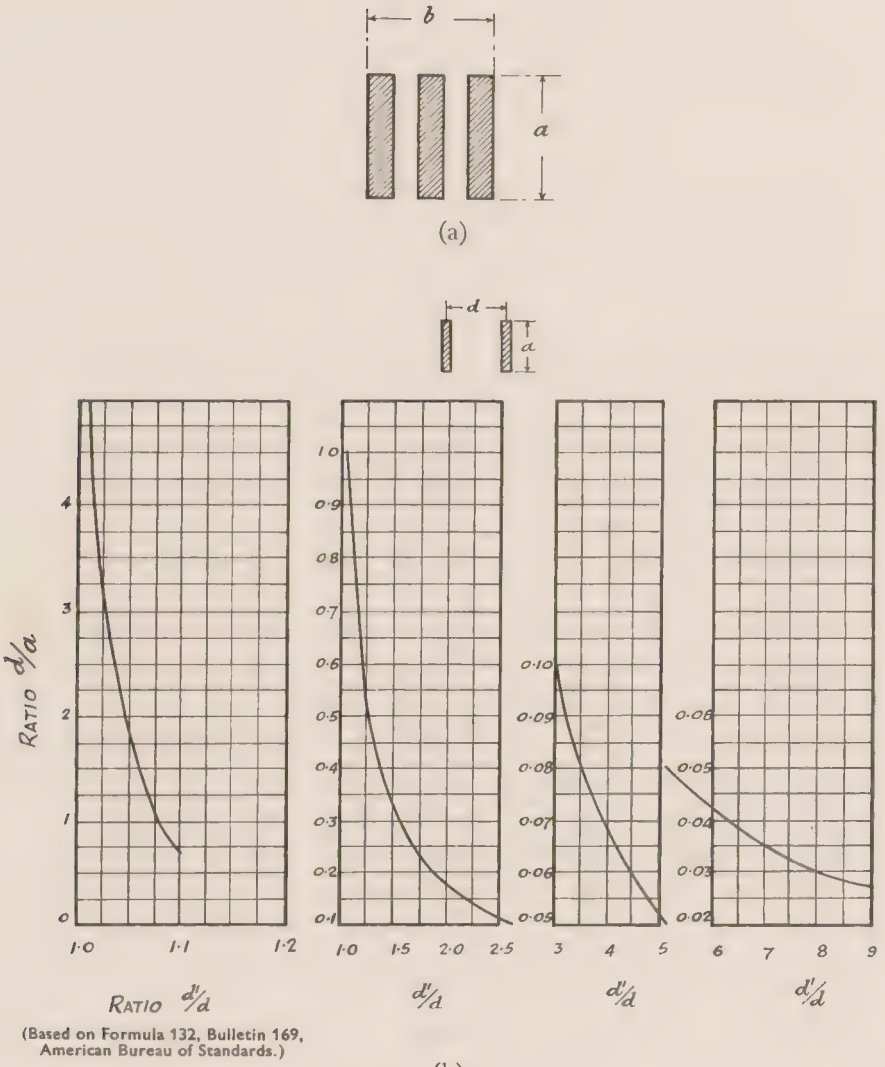

b
a
(a)
d
a
RATIO d/a
4
3
2
1
0
1·0
1·1
1·2
RATIO d'/d
(Based on Formula 132, Bulletin 169, American Bureau of Standards.)
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
1·0
1·5
2·0
2·5
d'/d
0·10
0·09
0·08
0·07
0·06
0·05
3
4
5
d'/d
0·06
0·05
0·04
0·03
0·02
6
7
8
9
d'/d
(b)

FIG. 13-38.

For this example, we have,

$a = 4$ inches.
$b = 1{\cdot}25$ inches.
$d/a = 5/4$ for phases A-B and B-C
$d/a = 10/4$ for phases A-C.
$S = 75 \times 12 = 900$ inches.

PHASE A.

$$\text{Self-Inductance } L_A = 2S\left(\text{Log}\epsilon\,\frac{2S}{R} - 1 + \frac{R}{S}\right)$$

$S = 900 \times 2{\cdot}54 = 2{,}286$ cm.
$R = 0{\cdot}2235\,(4 + 1{\cdot}25) \times 2{\cdot}54 = 2{\cdot}98$ cm.

$$L_A = 2 \times 2{,}286\left(\text{Log}\epsilon\,\frac{2 \times 2{,}286}{2{\cdot}98} - 1 + \frac{2{\cdot}98}{2{,}286}\right)$$
$$= 4{,}572\,(\text{Log}\epsilon\ 1{,}540 - 1 + 0{\cdot}0013)$$
$$= 29{,}000 \text{ cm.}$$

Mutual Inductance A to B (M_{AB})

$$M = 2S\left(\text{Log}\epsilon\,\frac{2S}{d'} - 1 + \frac{d'}{S}\right)$$

$d/a = 5/4 = 1{\cdot}25$.
From Fig. 13-38 d'/d for $1{\cdot}25 = 1{\cdot}07$
$\therefore\ d' = d \times 1{\cdot}07 \times 2{\cdot}54$ cm.
$= 5 \times 1{\cdot}07 \times 2{\cdot}54 = 13{\cdot}59$ cm.

$$M_{AB} = 2 \times 2{,}286\left(\text{Log}\epsilon\,\frac{2 \times 2{,}286}{13{\cdot}59} - 1 + \frac{13{\cdot}59}{2{,}286}\right)$$
$$= 4{,}572\,(\text{Log}\epsilon\ 336{\cdot}4 - 1 + 0{\cdot}006)$$
$$= 22{,}000 \text{ cm.}$$

Mutual Inductance A to C (M_{AC})

$d/a = 10/4 = 2{\cdot}5$
from Fig. 13-38 d'/d for $2{\cdot}5 = 1{\cdot}035$
$\therefore\ d' = d \times 1{\cdot}035 \times 2{\cdot}54$ cm.
$= 10 \times 1{\cdot}035 \times 2{\cdot}54 = 26{\cdot}30$ cm.

$$M_{AC} = 2 \times 2{,}286\left(\text{Log}\epsilon\,\frac{2 \times 2{,}286}{26{\cdot}3} - 1 + \frac{26{\cdot}3}{2{,}286}\right)$$
$$= 4{,}572\,(\text{Log}\epsilon\ 174 - 1 + 0{\cdot}011)$$
$$= 19{,}111 \text{ cm.}$$

The total inductance of Phase A is now the vectorial addition of the foregoing values, thus

$$\text{Total Inductance Phase A} = L_A - 0{\cdot}5\,M_{AB} + j0{\cdot}866\,M_{AB} - 0{\cdot}5\,M_{AC} - j0{\cdot}866\,M_{AC}$$
$$= 29{,}000 - (0{\cdot}5 \times 22{,}000) + j(0{\cdot}866 \times 22{,}000) - (0{\cdot}5 \times 19{,}111) - j(0{\cdot}866 \times 19{,}111)$$

which simplifies

$$\begin{aligned} L_A &= +29{,}000 \\ M_{AB} &= -11{,}000 + j19{,}225 \\ M_{AC} &= -9{,}555 - j16{,}500 \\ &\quad + 8{,}345 + j2{,}725 \text{ cm.} \end{aligned}$$

and the inductive reactance will be

$$\begin{aligned} X_L &= 2\pi f L \times 10^{-9} \text{ ohms.} \\ &= 2 \times \pi \times 50 \times 8{,}345 \times 10^{-9} \text{ ohms.} \\ &= 0{\cdot}00262 \text{ ohms.} \end{aligned}$$

Note that the j component is an energy component.

By symmetry Phase C will have the same inductance as Phase A, although as the j components are opposite in direction to Phase A, the actual reactive drops will not be the same. For all practical purposes similarity may be assumed without appreciable error.

PHASE B.

The self-inductance will be the same as Phase A.

Mutual inductance will be between B-A and B-C. Clearly B-A will have the same value as A-B, previously calculated. B-C will have an equal value but with reversed j component and the sum will be :

$$\begin{aligned} L_B &= +29{,}000 \\ M_{BA} &= -11{,}100 + j19{,}225 \\ M_{BC} &= -11{,}100 - j19{,}225 \\ &\quad + 6{,}800 \end{aligned}$$

$$\begin{aligned} X_L &= 2\pi f L \times 10^{-9} \\ &= 2\pi \times 50 \times 6{,}800 \times 10^{-9} \\ &= 0{\cdot}00214 \text{ ohms.} \end{aligned}$$

The full load current at 400 volts is 2,160 amperes and the reactive drop in each phase when carrying this current is :

$$\begin{aligned} \text{Phase A} &= 0{\cdot}00262 \times 2{,}160 = 5{\cdot}66 \text{ volts.} \\ \text{Phase B} &= 0{\cdot}00214 \times 2{,}160 = 4{\cdot}62 \text{ volts.} \\ \text{Phase C} &= 0{\cdot}00262 \times 2{,}160 = 5{\cdot}66 \text{ volts.} \end{aligned}$$

$$\text{Average reactive drop} = 15{\cdot}94/3 = 5{\cdot}313 \text{ volts.}$$

Expressed as a percentage of the line to neutral voltage, this is equal to

$$\frac{5{\cdot}313 \times 100}{230} = 2{\cdot}31\%$$

If, in the example used, we calculate the fault MVA by taking into account the reactance of the transformer alone we have

$$\frac{1{,}500 \times 100}{5{\cdot}6 \times 1{,}000} = 26{\cdot}8 \text{ MVA,}$$

If we now take into account the reactance of the conductors, we have

$$\frac{1{,}500 \times 100}{(5{\cdot}6 + 2{\cdot}31) \times 1{,}000} = 18{\cdot}96 \text{ MVA,}$$

showing a reduction of some 29% approx.

Earlier, the reduction to be expected due to the equivalent h.v. reactance has been demonstrated. If, in the foregoing example, we assume that the breaking capacity of the h.v. gear is 150 MVA, then the equivalent h.v. reactance on a 1,500 kVA base is,

$$\frac{1{,}500 \times 100}{150 \times 1{,}000} = 1{\cdot}0\%.$$

Including this in the short-circuit calculation we get,

$$\frac{1{,}500 \times 100}{(5{\cdot}6 + 2{\cdot}31 + 1{\cdot}0) \times 1{,}000} = 16{\cdot}84 \text{ MVA}$$

showing a reduction of some 37% on the short-circuit value arrived at by taking into account the transformer reactance only.

It has been indicated that resistance may play an important part in low-voltage calculations. In the foregoing example, the resistance drop, due to the conductors would be 0·41 volts per phase and this would not affect the answers very considerably. On the other hand, a smaller section might have resistance values which affect the answer -for example, we find that a cable of 0·10 nominal cross-section has a reactance of 0·11536 ohms per mile per core and a resistance of 0·4534 ohms per mile per core. The latter is then four times the reactance and from what has been stated on page 247, must be taken into account. From the formula

$$\text{Impedance} = \sqrt{\text{Resistance}^2 + \text{Reactance}^2}$$

we find that the impedance of the 0·1 sq. inch cable is 0·4504 ohms and it is this value which should be included in the short-circuit calculation instead of the reactance of 0·11536 ohms. In doing so, however, care must be taken to add the transformer and conductor values, thus

$$\begin{aligned} \text{Transformer} &= O + jX_1 \\ \text{Conductor} &= R + jX_2 \end{aligned}$$

$$\begin{aligned} \text{Total} &= \overline{R + j\,(X_1 + X_2)} \\ &= \sqrt{R^2 + (X_1 + X_2)^2} \end{aligned}$$

the O indicating that resistance in the transformer is ignored.

In order to avoid the laborious arithmetic outlined earlier for the calculation of reactance for bar copper conductors, the author has produced the following table* :—

**First published in an article by the Author in the "Electrical Review," to whom acknowledgment is made for permission to reproduce here.*

TABLE I

No. of straps and section.	Phase centres In.	Reactance factor Kx.	Resistance factor Kr.
1, 2in. × ¼in.	3	3·871	1·67
	4	4·421	
	5	4·85	
	6	5·24	
2, 2in. × ¼in.	3	3·488	0·83
	4	4·038	
	5	4·465	
	6	4·812	
	7	5·107	
	8	5·366	
3, 2in. × ¼in.	4	3·717	0·55
	5	4·144	
	6	4·493	
	7	4·79	
	8	5·043	
	9	5·27	
1, 3in. × ¼in.	3	3·17	1·1
	4	3·717	
	5	4·144	
	6	4·493	
2, 3in. × ¼in.	3	2·895	0·55
	4	3·45	
	5	3·871	
	6	4·22	
	7	4·515	
	8	4·77	
3, 3in. × ¼in.	4	3·21	0·37
	5	3·631	
	6	3·981	
	7	4·275	
	8	4·53	
	9	4·755	
4, 3in. × ¼in.	5	3·386	0·275
	6	3·768	
	7	4·062	
	8	4·317	
	9	4·542	
	10	4·744	
1, 4in. × ¼in.	3	2·75	0·83
	4	3·21	
	5	3·631	
	6	3·981	
	7	4·275	
	8	4·53	
	9	4·755	
2, 4in. × ¼in.	3	2·59	0·42
	4	2·993	
	5	3·386	
	6	3·768	
	7	4·062	
	8	4·317	
	9	4·542	
3, 4in. × ¼in.	5	3·29	0·275
	6	3·577	
	7	3·871	
	8	4·13	
	9	4·351	
	10	4·553	
	11	4·735	
	12	4·901	
4, 4in. × ¼in.	6	3·403	0·21
	7	3·70	
	8	3·952	
	9	4·18	
	10	4·378	
	12	4·728	
	15	5·153	
6, 4in. × ¼in.	9	3·871	0·138
	10	4·072	
	12	4·421	
	15	4·844	
	18	5·196	
2, 6in. × ¼in.	4	2·322	0·275
	5	2·75	
	6	3·10	
	7	3·39	
	8	3·65	
	9	3·871	
	10	4·072	
4, 6in. × ¼in.	6	2·833	0·138
	7	3·13	
	8	3·382	
	9	3·61	
	10	3·81	
	12	4·157	
	15	4·58	
	18	4·931	
6, 6in. × ¼in.	10	3·577	0·092
	11	3·758	
	12	3·93	
	15	4·351	
	18	4·70	
	21	5·00	
	24	5·257	

Phases in horizontal plane. Multiple bars spaced ¼ in. All figures based on a frequency of 50 cycles per second.

With this table, we use the formula,

$$\%\ \text{Reactance (or Resistance) at given kVA base} = \frac{\text{kVA base} \times \text{Kx (or Kr)} \times \text{L}}{(\text{V})^2}$$

where Kx = reactance factor from table
Kr = resistance factor from table
L = length of conductor run in feet
V = line voltage

If in a run of conductors, a variation of phase spacing or in conductor section occurs, a separate calculation is necessary for each spacing or section, adding the results to obtain the total. Where odd centres such as $5\frac{1}{4}$ or $7\frac{1}{2}$ inches are found, calculations should be made using factors for the nearest spacing *less* than the actual. Results thus obtained will be on the safe side. If short-circuit calculations are being made by the ohmic method, the ohmic values per foot of conductor can be obtained from the table by multiplying any factor Kx or Kr by 10^{-5}.

For the purpose of approximate calculations, in the absence of actual data from the manufacturers, the following reactances may be used for machines and transformers. Tables for cables and overhead lines are included in the section " Useful Data."

TABLE II

Reactance of Machines

Turbo-Alternator ..	15–20%
Salient Pole Alternator	20–33%
Synchronous Motors	10–12%

TABLE III

Reactance of Transformers

100– 250 kVA	4·2%
251– 500 ,,	4·4%
501– 750 ,,	4·7%
751–1,000 ,,	5·0%
1,001–1,500 ,,	5·3%
1,501–2,000 ,,	5·6%
2,001–3,000 ,,	6·0%
3,001–4,000 ,,	6·4%
4,001–5,000 ,,	6·8%
5,001–7,500 ,,	7·3%
7,500 upwards	10·0%

All above values are at 50 cycles.

Determination of Asymmetrical Values of Short-Circuit Current.

So far, all values of short-circuit current calculated have been on the assumption of symmetrical conditions. In any short-circuit, at least one of the three phases will show asymmetry, the degree of being determined by the position on the voltage wave at which the fault occurs, and by the ratio of reactance to resistance.

In circuits where reactance largely predominates (*e.g.*, generators and transformers) and a fault occurs at zero voltage, the fault current may be analysed into two components, an a.c. component equal to the voltage divided by the reactance, and a d.c. component which, at zero time is equal to the a.c. component and which dies away rapidly in accordance

with an exponential law having a time-constant equal to the ratio of inductance to resistance.

The combination of the a.c. and d.c. components is referred to as the asymmetrical current, while the a.c. component alone is termed the symmetrical current. When a fault occurs at an instant of maximum voltage, the d.c. component is almost zero.

In the first condition, *i.e.*, zero voltage at the instant of fault, the asymmetrical current reaches its first peak at the end of the first half-cycle. In this time, the d.c. component has been reduced to about 80% of its initial value while the a.c. component has not diminished. This assumes a power factor of the short-circuit of 0·07. The value of the peak current is then 2·55 times the r.m.s. value of the initial symmetrical current. The multiplier 2·55 represents $1{\cdot}414 \times 1{\cdot}8$, the former being $\sqrt{2}$, the latter the doubling factor.

In circuits where resistance is of consequence, *e.g.*, at the ends of feeders, etc., the degree of asymmetry is reduced and the doubling factors for various ratios R/X are given as follows:

R/X	Doubling Factor
Very small	1·8
0·1	1·6
0·2	1·45
0·3	1·34
0·4	1·26
0·5	1·2
0·6	1·16
0·7	1·12
0·8	1·1
0·9	1·08
1·0	1·06

The power factor of the short-circuit may be roughly determined from the ratio,

$$\frac{\text{Resistance}}{\text{Impedance}}$$

The importance of asymmetrical values of short-circuit current lie more in relay application than in circuit-breaker selection. The " making " current, however, when closing a circuit-breaker on to an existing fault is the peak current in the first half-cycle and the greater the asymmetry, the greater the making current. In relay application, knowledge of the current at different times is essential with time-delay relays. Here the use of standard decrement curves is useful and details of these are given in Chapter XXI, and in " The Switchgear Handbook," Vol.2 (see Bibliography).

Calculation of Unsymmetrical Short-Circuits.

It has already been stated that for the purpose of selecting suitably rated circuit-breakers the determination of fault values based on a symmetrical condition, *i.e.*, a three-phase fault, is sufficient. This method is also adequate for determining overcurrent factors for current transformers, forces on conductor systems and protective gear stability ratios. For the purpose of determining relay settings for earth faults, and for the more advanced forms of protective gear and for investigating the transient stability of an

interconnected power system, the unsymmetrical condition is important in that it is essential to have a knowledge of the values of short-circuit current due to faults between two lines or faults between one line to earth and to study the distribution of these currents throughout the network. In order to calculate short-circuit currents on this basis, use has to be made of the method of symmetrical components, the principles of which were originally enumerated by Stovkis and later (1918) in more practical form by Fortescue.

The theoretical treatment of symmetrical components is beyond the scope of this volume and the reader is advised to refer to the many excellent works in existence, some of which are noted in the bibliography to this chapter. For our purpose, the theory is accepted and we shall confine ourselves to demonstrating the practical use of symmetrical components to determine fault currents due to line/line or line/earth faults. No attempt will be made to cover the calculation of unsymmetrical voltages although it will be clear that these are important, particularly in protective systems of the directional type where voltage plays an important part. The recommended works for a study of voltage calculations are included in the bibliography, and the present chapter must be regarded as an introduction to the subject only.

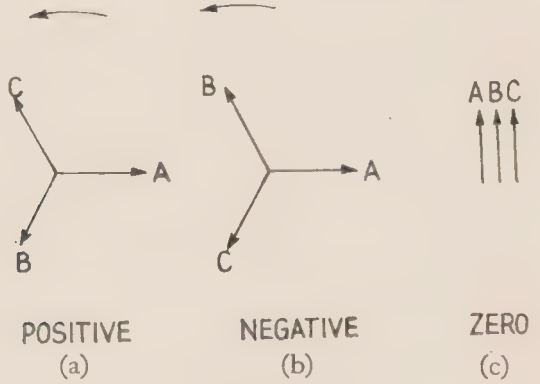


FIG. 13-39.

In studying the subject, certain established facts may be stated :—

(1) In any three-phase system the occurrence of a fault causes unbalance, the currents and voltages becoming unequal in magnitude, while the vectors representing them are no longer spaced 120° or equal.

(2) In any unbalanced system, it is possible to analyse that system into two or three balanced systems known as positive, negative, and zero phase sequences.

(3) The positive phase sequence system is that system in which the phase or line currents or pressures reach a maximum in the same cyclic order as those in a normal supply, *e.g.*, assuming the conventional counter-clockwise rotation, then the positive phase sequence vectors are those shown at (*a*) in Fig. 13-39. A balanced system corresponding to normal conditions contains a positive phase sequence only. It is also the condition for a three-phase fault.

(4) The negative phase sequence system is that system in which the vectors still rotate anti-clockwise but reach a maximum in a reverse order, *i.e.*, A.C.B. as indicated at (*b*) Fig. 13-39. Such a sequence can only arise from a line to line fault, in which the fault currents are confined to the faulted lines. Such a fault causes an unbalanced system containing positive and negative phase sequences, the former due to normal loading, the latter due to fault loading.

(5) The zero phase sequence system is a single phase vector system combining three equal vectors in phase, as shown at (*c*) Fig. 13-39, and represents the residual current or pressure present under fault conditions on a three-phase system with a fourth wire or earth return present. Clearly the zero phase sequence embraces the ground therefore, in addition to the three line wires and represents a fault condition to earth or to a fourth conductor if present. Its presence arises only where fault to earth currents can return to the system via the star point of that system or via an artificial neutral point provided to earth a delta system. In an earth fault, positive and negative phase sequences are also present.

From this simple outline, it is possible to see that the segregation of the sequence components allow for an intelligent estimate of fault currents and voltages under three fault conditions, viz. :—

(*a*) The three-phase fault, involving the positive phase sequence only.

(*b*) Single phase line to line fault involving the positive and negative phase sequences.

(*c*) Single phase line to earth fault involving positive, negative and zero phase sequences.

It will be shown in examples worked out later that different values of fault current occur for the different fault conditions, and it is this which demonstrates the need for calculation by the symmetrical components method in order to determine relay settings for various fault conditions.

That the values of current should differ is due to the fact that the impedances or reactances to the three sequence currents differ and before proceeding to illustrate the use of symmetrical components, some idea of the values of these impedances or reactances will be valuable.

In all *static* plant and in networks, the positive and negative phase sequence impedances or reactances are equal but may differ to the zero phase sequence impedance or reactance. In *rotating* plant, all three are different.

Static plant, *e.g.*, transformers, have positive and negative phase sequence impedances equal to the normal three-phase impedance usually quoted by the manufacturer and are the values given in Table III. The zero phase sequence impedance varies with the transformer connection. For delta/star (star neutral earthed), star/star (both neutrals earthed), star or delta/inter star (inter star neutral earthed), the zero phase sequence impedance is equal to the positive or negative phase sequence impedance. For star/star with three wire primary, the zero phase sequence impedance will be approximately 0·66 times the positive or negative value, provided a three limbed core is used. In the three-phase shell type of transformer, or in a group of three single-phase transformers, the zero phase sequence impedance is very high, due to low reluctance return flux paths and may be as high as four times the positive or negative values.

For all other transformer connections open circuit to zero phase sequence currents can be assumed.

Static networks, a term denoting cables and overhead lines, have positive and negative phase sequence impedances equal to the normal and may be taken from the tables in " Useful Data."

Zero phase sequence impedances however vary considerably and involve a separate study. The variation depends on such factors as whether cables are laid separately or bunched, how laid, etc. For overhead lines, values vary for single and double circuit lines, with or without earth wires, and again whether the earth wire is magnetic or non-magnetic.

For approximation, the following values for a single three-phase overhead line are useful and are quoted from " The Switchgear Handbook," Vol. 2 (see Bibliography).

With no earth wire $Z_0 = 3{\cdot}5\ Z_1$ or Z_2
With light steel earth wire $Z_0 = 3{\cdot}5\ Z_1$ or Z_2
With non-magnetic earth wire $Z_0 = 2Z_1$ or Z_2

where Z_0 = Zero Phase Sequence Impedance.
Z_1 = Positive Phase Sequence Impedance.
Z_2 = Negative Phase Sequence Impedance.

For rotating plant, the positive phase sequence impedance will be, generally, the subtransient, transient, or synchronous impedance, depending on the purpose of calculation. For most purposes the subtransient value, normally quoted by manufacturers will be used. In case of long time delay applied to a protective system, the synchronous, or steady state, value may be necessary, as after several seconds, the steady short-circuit condition is reached. Alternatively, standard decrement curves can be applied to the initial values of short-circuit current.

The negative phase sequence impedance differs from the positive to an extent dependent on the type of winding and is generally less than the positive value.

As so much depends on design and type, variations are to be found in most books dealing with symmetrical components and it is therefore essential that a definite value be obtained for a particular machine. As we are only concerned with demonstrating the use of symmetrical components it will suffice if we assume an average figure of 0·73 times the positive phase sequence impedance. Similar considerations concern the zero phase sequence impedance for rotating machines. For example, Robertson gives typical values as 0·33 times the positive value, Wagner and Evans give values from 1 to 25%, while Mortlock gives a range from 4·5 to 13% (percentage values being actual zero phase sequence impedances). As we are not concerned, in the examples which follow, with the zero phase sequence impedance of any rotating plant, no attempt will be made to determine a value.

When additional impedance is inserted in the neutral connection to earth, *e.g.*, earthing resistance or reactance, the zero phase sequence impedance of this is three times the actual value.

In the notation Z_1, Z_2, Z_0, which will be used to denote the three impedances, Z will be $R + jX$ where $R = O$, *i.e.*, resistance will be ignored, but as noted earlier in three-phase fault calculations, resistance may be a factor in cables and overhead lines. It is omitted here for simplicity only.

In determining fault values for the rating of circuit-breakers, etc., it is

only necessary to calculate for the worst condition, *i.e.*, maximum fault current to be broken by the circuit-breaker. For relay settings, however, it is essential that these be arranged to take care of minimum fault conditions as well as maximum.

For example, it is essential to ensure that an earth fault relay will operate not only when all plant is in service, but also when only a minimum of plant may be connected.

As a first example, let us assume a simple network as shown in Fig. 13-40.

For the purpose of our calculations, we may adopt the ohmic method and it is required to ascertain the fault currents for a fault at F, under two

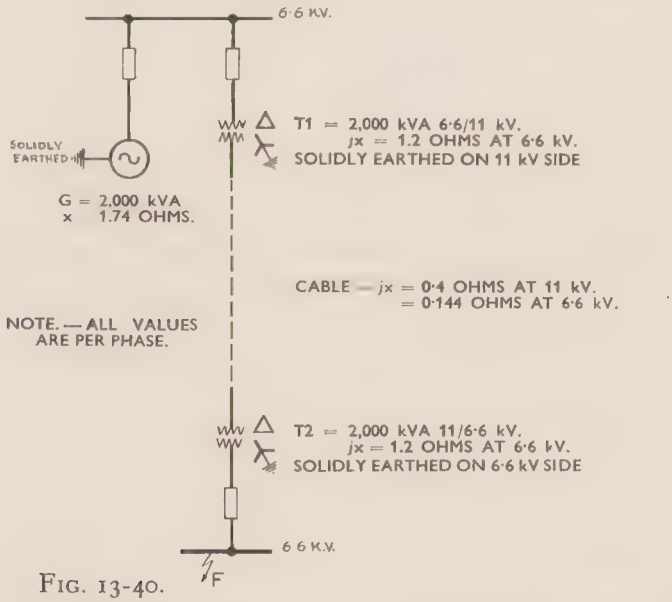

6·6 KV.
T1 = 2,000 kVA 6·6/11 kV.
jx = 1.2 OHMS AT 6·6 kV.
SOLIDLY EARTHED ON 11 kV SIDE
SOLIDLY EARTHED
G = 2,000 kVA
x 1.74 OHMS.
CABLE — jx = 0·4 OHMS AT 11 kV.
= 0·144 OHMS AT 6·6 kV.
NOTE. — ALL VALUES ARE PER PHASE.
T2 = 2,000 kVA 11/6·6 kV.
jx = 1.2 OHMS AT 6·6 kV.
SOLIDLY EARTHED ON 6·6 kV SIDE
6·6 KV.
F

FIG. 13-40.

conditions, *i.e.*, line to line and line to earth. As explained on page 268, it is necessary, when calculating in ohms, to work to a base voltage. As the assumed fault occurs on the 6·6 kV bars at the remote substation, it will be convenient to choose this voltage for the base.

The generator of 2,000 kVA has a reactance of 8%, and this has already been shown on page 268 to be equal to 1·74 ohms at 6·6 kV. There are two transformers, both of 2,000 kVA with a reactance of 5·6%. Converting to ohms at 6·6 kV gives,

$$\frac{5{\cdot}6 \times 10 \times 6{\cdot}6^2}{2{,}000} = 1{\cdot}2 \text{ ohms.}$$

The cable between the two transformers has a reactance of 0·4 ohms at 11 kV.

Referred to the 6·6 kV base we get,

$$\left(\frac{6{,}600}{11{,}000}\right)^2 \times 0{\cdot}4 = 0{\cdot}144 \text{ ohms.}$$

Thus we have the following values :—

Z_1 Generator—Positive Phase Sequence Impedance $= 0 + j1{\cdot}74$ ohms.
Z_2 ,, —Negative ,, ,, ,, $= (0 + j1{\cdot}74) \times 0{\cdot}73$
$= 0 + j1{\cdot}27$ ohms.

Z_1 Transformer No. 1
—Positive Phase Sequence Impedance $= 0 + j1{\cdot}2$ ohms.
Z_2 ,, —Negative ,, ,, ,, $= 0 + j1{\cdot}2$ ohms.
Z_1 Cable —Positive Phase Sequence Impedance $= 0 + j0{\cdot}144$ ohms.
Z_2 ,, —Negative ,, ,, ,, $= 0 + j0{\cdot}144$ ohms.

Z_1 Transformer No. 2
—Positive Phase Sequence Impedance $= 0 + j1.2$ ohms.
Z_2 ,, —Negative ,, ,, ,, $= 0 + j1{\cdot}2$ ohms.
Z_0 ,, —Zero ,, ,, ,, $= 0 + j1{\cdot}2$ ohms.

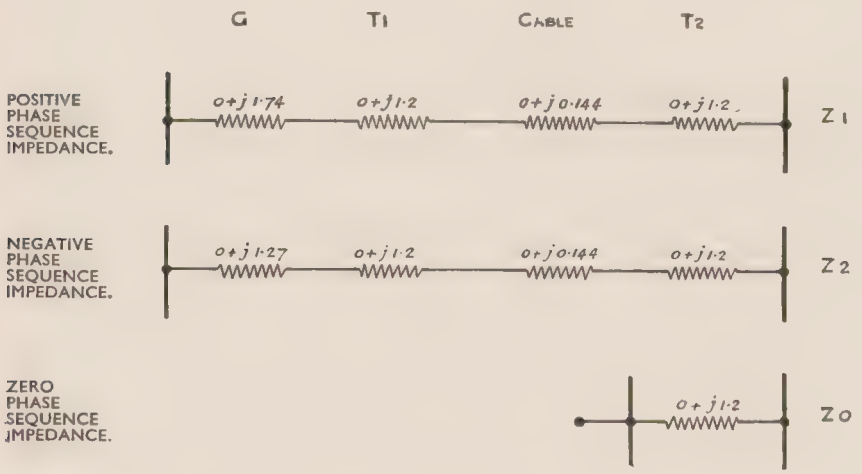


FIG. 13-41.

It will be noted that the only area where zero phase sequence current can appear is at Transformer No. 2, *i.e.*, from a line fault to earth at F back to the 6·6 kV neutral of this transformer via the ground.

The conditions for the three sequences can now be set down as indicated in Fig. 13-41 and adding the various impedances in series arithmetically, obtain :—

	Z_1	Z_2	Z_0
Generator	$0 + j1{\cdot}74$	$0 + j1{\cdot}27$	—
Transformer (1)	$0 + j1{\cdot}2$	$0 + j1{\cdot}2$	—
Cable	$0 + j0{\cdot}144$	$0 + j0{\cdot}144$	—
Transformer (2)	$0 + j1{\cdot}2$	$0 + j1{\cdot}2$	$0 + j1{\cdot}2$
	$0 + j4{\cdot}284$	$0 + j3{\cdot}814$	$0 + j1{\cdot}2$

With these values, we can proceed to calculate for the two fault conditions as follows.

LINE TO EARTH FAULT.

As explained earlier, faults to earth embrace the three sequence components and therefore the total impedance to the fault will be,

$$\begin{aligned} Zt &= Z_1 + Z_2 + Z_0 \\ &= 0 + j4{\cdot}284 + 0 + j3{\cdot}814 + 0 + j1{\cdot}2 \\ &= 0 + j9{\cdot}298 \text{ ohms.} \end{aligned}$$

The earth fault current will be

$$If = \frac{3\,E}{Z\,t}$$

where E = Normal line to neutral voltage of the selected base voltage.

$$\therefore If = \frac{3 \times 3{,}810}{9{\cdot}298} = 1{,}227 \text{ amperes.}$$

The condition at the fault can be shown as in Fig. 13-42.

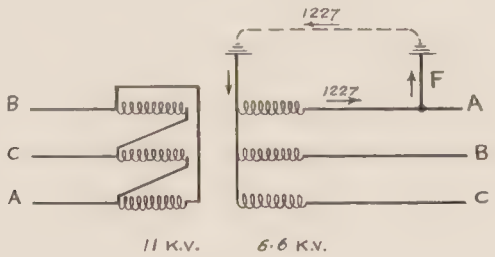


FIG. 13-42.

LINE TO LINE FAULT.

In this case, only the positive and negative phase sequence impedances will limit the fault and

$$\begin{aligned} Zt &= Z_1 + Z_2 \\ &= 0 + j4{\cdot}284 + 0 + j3{\cdot}814 \\ &= 0 + j8{\cdot}098 \text{ ohms} \end{aligned}$$

$$\text{and } If = \frac{\sqrt{3}\,E}{Z\,t}$$

$$= \frac{\sqrt{3} \times 3{,}810}{8{\cdot}098} = 817 \text{ amperes.}$$

The condition at the fault can be shown as in Fig. 13-43.

We have seen, therefore, that there is a considerable difference in fault current as between line to earth and line to line faults, and any protective gear installed must be sensitive to these different values. By a calculation similar to those undertaken earlier it can be shown that the three-phase fault current at F would be 887 amperes, so that there are three different values for different fault conditions.

In the calculation for a line to earth fault, the resistance to ground has been assumed zero. This is a condition which is unlikely as, apart from

any resistance which may be purposely installed in the neutral connection to limit the earth fault current, *e.g.*, to twice full load current with line to neutral voltage impressed, there must be resistance at the connection to ground. Let us assume that this is 2 ohms and this has to be multiplied by three. *

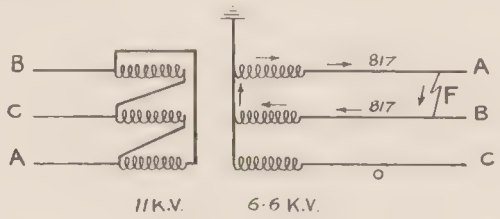
For a line to earth fault, the total impedance will now be,

$$\begin{aligned} Zt &= 0 + j4{\cdot}284 + 0 + j3{\cdot}814 + 6 + j1{\cdot}2 \\ &= 6 + j9{\cdot}298 \\ &= \sqrt{6^2 + 9{\cdot}298^2} = 11 \text{ ohms (approx.).} \end{aligned}$$

$$\text{and If} = \frac{3 \times 3{,}810}{11} = 1{,}039 \text{ amperes.}$$

as compared with 1,227 amperes previously calculated with zero resistance.

Having determined the fault current conditions at the fault, as shown in Figs. 13-42 and 13-43, it is necessary to ascertain the distribution of current back to the source.



T2

FIG. 13-43.

LINE TO EARTH FAULT.

The positive, negative and zero phase sequence currents in the fault are equal and each are one-third of If, so that

$$If_1 = If_2 = If_0 = If/3,$$

and in the faulty phase, the total fault current If_A is the sum of the three sequence currents I_1, I_2 and I_0 and

$$If_1 + If_2 + If_0 = If = If_A.$$

The total fault current in the phases B and C is given by,

$$If_B = I_0 + a^2I_1 + aI_2$$
$$If_C = I_0 + aI_1 + a^2I_2$$

where the vector operators a and a^2 are

$$a = -\tfrac{1}{2} + j\frac{\sqrt{3}}{2} = -0{\cdot}5 + j0{\cdot}866$$

$$a^2 = -\tfrac{1}{2} - j\frac{\sqrt{3}}{2} = -0{\cdot}5 - j0{\cdot}866$$

so that,

$$\begin{aligned} If_B &= I_0 + I_1(-0{\cdot}5 - j0{\cdot}866) + I_2(-0{\cdot}5 + j0{\cdot}866) \\ &= I_0 - 0{\cdot}5(I_1 + I_2) - j0{\cdot}866(I_1 - I_2) \\ If_C &= I_0 + I_1(-0{\cdot}5 + j0{\cdot}866) + I_2(-0{\cdot}5 - j0{\cdot}866) \\ &= I_0 - 0{\cdot}5(I_1 + I_2) + j0{\cdot}866(I_1 - I_2) \end{aligned}$$

* *If the value of earth resistance is R, then the equivalent resistance inserted in each branch of the network in series with the zero sequence impedance is 3R.*

In the example, a 6·6 kV star base has been used. To obtain the true currents at 11 kV, *i.e.*, in the secondary of T_1 and the primary of T_2, account must be taken of the phase displacement which occurs in respect to the 6·6 kV star base. The equations for such conversions are as follows, which should be read in conjunction with Fig. 13-44.

$$I'_a = n\,(I''_b - I''_c) = I'_B - I'_c$$
$$I'_b = n\,(I''_c - I''_a) = I'_C - I'_A$$
$$I'_c = n\,(I''_a - I''_b) = I'_A - I'_B$$

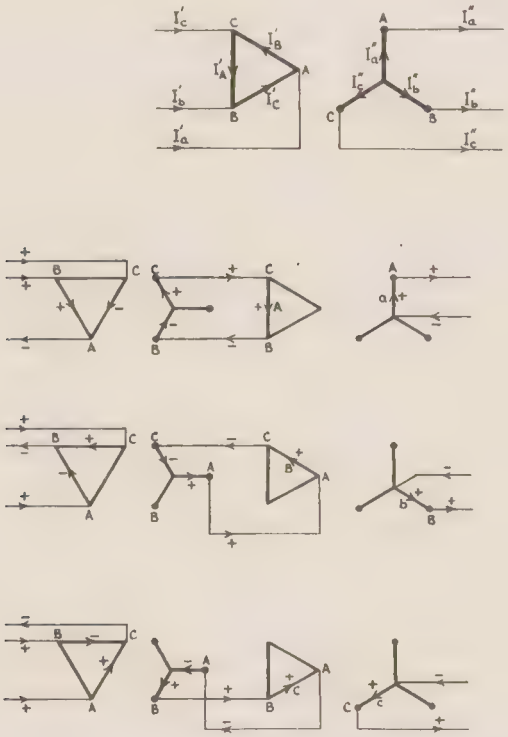


FIG. 13-44.

where n equals the turns per phase ratio of transformation in the direction of transformation being considered and

I'_a I'_b I'_c = Converted line currents being sought,

I''_a I''_b I''_c = Line currents on star base.

With this essential data, the calculations are as follows, using the total value to earth of 1,227 amperes.

If_1 = Positive Sequence Network Current = 1227/3 = 409 amps.

If_2 = Negative Sequence Network Current = 1227/3 = 409 amps.

If_0 = Zero Sequence Network Current = 1227/3 = 409 amps.

If_A in Secondary Line T2 $= If_1 + If_2 + If_0 = 1227$ amps.
If_B in Secondary Line T2 $= I_0 + a^2I_1 + aI_2$
$= I_0 - 0{\cdot}5\ (I_1 + I_2) - j0{\cdot}866\ (I_1 - I_2)$
$= 409 - 0{\cdot}5\ (818) - j0{\cdot}866\ (0)$
$= 409 - 409 = 0$ amps.
If_C in Secondary Line T2 $= I_0 + aI_1 + a^2I_2$
$= I_0 - 0{\cdot}5\ (I_1 + I_2) + j0{\cdot}866\ (I_1 - I_2)$
$= 409 - 0{\cdot}5\ (818) + j0{\cdot}866\ (0)$
$= 409 - 409 = 0$ amps.
If_A in Primary Line T2 $= -0{\cdot}346\ (0-0) = 0$ amps.
If_B in Primary Line T2 $= -0{\cdot}346\ (0 - 1{,}227) = 424{\cdot}5$ amps.
If_C in Primary Line T2 $= -0{\cdot}346\ (1{,}227 - 0) = -424{\cdot}5$ amps.

NOTE.—0·346 is the turns per phase ratio of transformation, *i.e.*,

$$\frac{3{,}810}{11{,}000} = 0{\cdot}346$$

The minus sign before the turns ratio indicates a reversal of line currents brought about by the cascade delta/star transformations.

If_A in Primary Line T1 $= -0{\cdot}96\ (424{\cdot}5-(-424{\cdot}5)) = -818$ amps.
If_B in Primary Line T1 $= -0{\cdot}96\ (-424{\cdot}5 - 0) = 409$ amps.
If_C in Primary Line T2 $= -0{\cdot}96\ (0 - 424{\cdot}5) = 409$ amps.

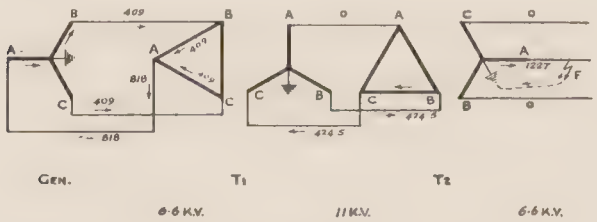


FIG. 13-45.

NOTE.—0·96 is the turns per phase ratio of transformation, *i.e.*,

$$\frac{11{,}000}{6{,}600 \times 1{\cdot}73} = 0{\cdot}96$$

Where positive values of current appear, this indicates flow in the direction of the fault. Negative values indicate flow in the opposite direction.

The values of current having now been calculated in each line for the complete network up to the fault, the values may be conveniently shown in a diagram as Fig. 13-45.

LINE TO LINE FAULT.

It has been shown (page 285) that a fault between lines A and B has a current value of 817 amperes. There will be no current in line C. For the line to line condition, the positive and negative phase sequences only are involved and the sequence currents I_1 (positive) and I_2 (negative) are,

$I_1 = \frac{1}{3}\ (I_A + aI_B + a^2I_C)$
$= \frac{1}{3}\ [I_A + I_B\ (-0{\cdot}5 + j0{\cdot}866) + I_C\ (-0{\cdot}5 - j0{\cdot}866)]$
$= \frac{817 - 817\ (-0{\cdot}5 + j0{\cdot}866) + 0}{3}$

$$= \frac{817 + 408{\cdot}5 - j708}{3} = 408{\cdot}5 - j236$$

$$I_2 = \tfrac{1}{3}(I_A + a^2 I_B + a I_C)$$
$$= \tfrac{1}{3}[I_A + I_B(-0{\cdot}5 - j0{\cdot}866) + I_C(-0{\cdot}5 + j0{\cdot}866)]$$
$$= \frac{817 - 817(-0{\cdot}5 - j0{\cdot}866) + 0}{3}$$
$$= \frac{817 + 408{\cdot}5 + j708}{3} = 408{\cdot}5 + j236$$

The total fault current is the sum of the two sequence network currents, thus,

$$I_1 = 408{\cdot}5 - j236$$
$$I_2 = 408{\cdot}5 + j236$$
$$If = 817 \text{ amperes.}$$

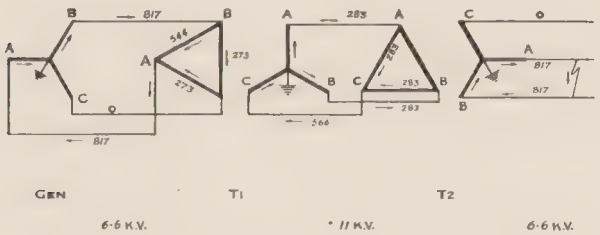


FIG. 13-46.

The currents in the line throughout the complete circuit can be solved as follows :—

I_A in Secondary Line T2	= 817 amps.	
I_B in Secondary Line T2	= —817 amps.	
I_C in Secondary Line T2	= 0 amps.	
I_A in Primary Line T2	= —0·346 (—817 —0)	= 283 amps.
I_B in Primary Line T2	= —0·346 (0—817)	= 283 amps.
I_C in Primary Line T2	= —0·346 (817—(—817))	= —566 amps.
I_A in Primary Line T1	= —0·96 (283—(—566))	= —817 amps.
I_B in Primary Line T1	= —0·96 (—566—283)	= 817 amps.
I_C in Primary Line T1	= —0·96 (283—283)	= 0 amps.

The values may now be included in a diagram of the network as show in Fig. 13-46.

The purpose of calculations such as the foregoing, for line to earth, and line to line faults may be seen by an inspection of the two diagrams Figs. 13-45 and 13-46. In these we see the currents at each point in the network for faults at a remote point.

It is clear that unless some form of discriminating protection be applied, there is every indication that, for a fault at the point chosen for our example, the Generator and the Transformers will all be disconnected by the through

fault current. For example, the normal current of the generator is 175 amperes, and for both types of fault, currents considerably in excess of normal are experienced. If simple overcurrent be fitted, high settings would be essential to avoid operation.

A second example may be worked using the percentage reactance method and a common kVA base. For this purpose, a system is shown in Fig. 13-47 and it will be our task to ascertain the fault current at a point close up to the 400 volt busbars at Substation C, on the occurrence of an earth fault between phase A and ground. The reactances indicated in the diagram are

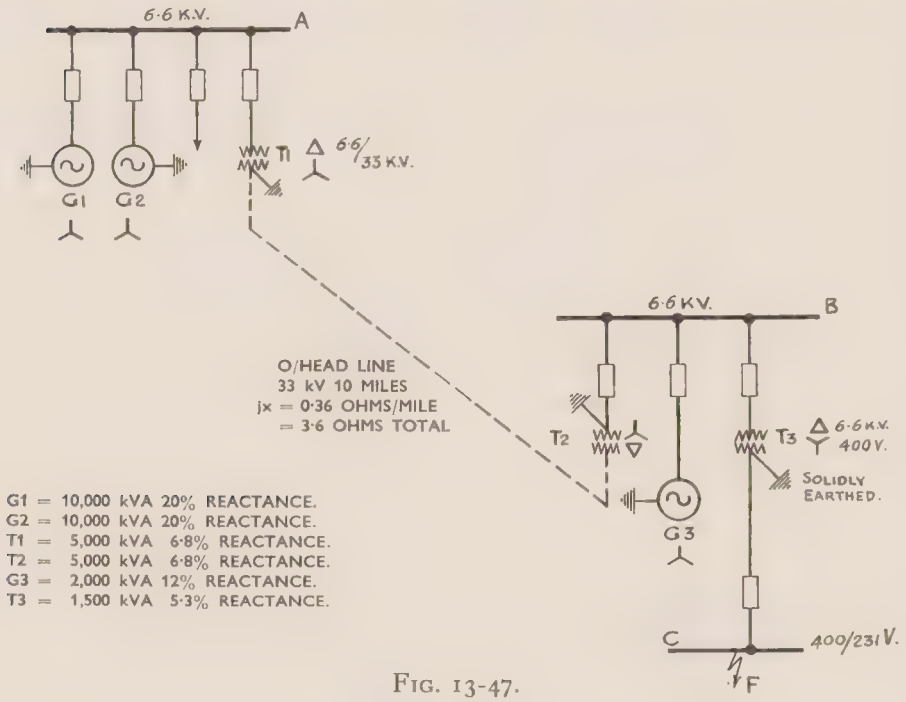


FIG. 13-47.

those to the positive phase sequence currents. The first task, as in three-phase fault calculations, is to convert all reactances to a common base, *i.e.*, 100,000 kVA as follows :—

$$\text{Generators G1 and G2} = \frac{100{,}000}{10{,}000} \times 20 = 200\% \text{ each}$$

$$\text{Transformers T1 and T2} = \frac{100{,}000}{5{,}000} \times 6{\cdot}8 = 136\% \text{ each}$$

$$\text{Overhead Line} = \frac{100{,}000 \times 100{,}000}{(33{,}000)^2} \times 3{\cdot}6 = 33\%$$

$$\text{Generator G3} = \frac{100{,}000}{2{,}000} \times 12 = 600\%$$

$$\text{Transformer T3} = \frac{100{,}000}{1{,}500} \times 5{\cdot}3 = 353\%$$

The positive, negative and zero phase sequence reactances are :—

	Z_1	Z_2	Z_0
Generators G1, G2 ..	200%	146%	—
Transformers T1, T2 ..	136%	136%	—
Overhead Line ..	33%	33%	—
Generator G3	600%	438%	—
Transformer T3 ..	353%	353%	353%

Following the procedure when calculating three-phase symmetrical faults, a series of network reduction diagrams are deduced in order that a single reactance to the fault may be ascertained. In this case, however, separate diagrams are required for each of the phase sequences, and Fig. 13-48 is a set of reactance diagrams for the original network. These can be reduced at once, by combining parallel values, and adding series values, to Figs. 13-49 and 13-50.

Values in parallel in Fig. 13-50 are evaluated as follows.

$$\text{Positive Network } \frac{1}{\frac{1}{405} + \frac{1}{600}} = 241\%$$

$$\text{Negative Network } \frac{1}{\frac{1}{378} + \frac{1}{438}} = 203\%$$

and the network diagrams now become Fig. 13-51. From this we determine that,

$$Z_1 = 594\%$$
$$Z_2 = 556\%$$
$$Z_0 = 353\%$$

and the total reactance (Zt) to the fault is

$$Zt = Z_1 + Z_2 + Z_0 = 1{,}503\%$$

and the fault current to earth is

$$If = \frac{3I \times 100}{Zt}$$

where I is the current due to 100,000 kVA at 400 volts, *i.e.*, 144,000 amperes, and

$$If = \frac{3 \times 144{,}000 \times 100}{1{,}503} = 28{,}800 \text{ amps.}$$

Thus for a fault to earth at a point close up to the 400 volt busbar we have the condition shown in Fig. 13-52.

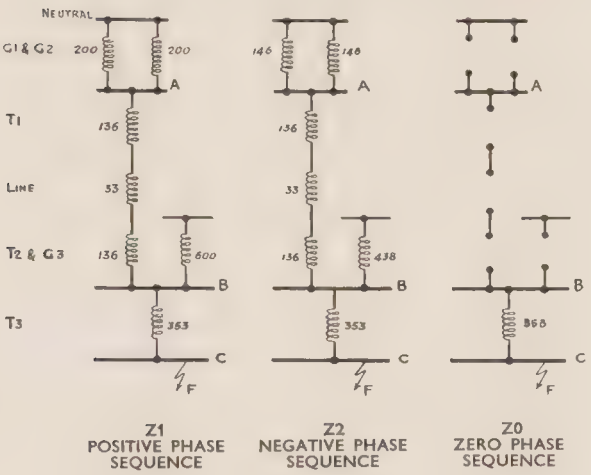


FIG. 13-48.

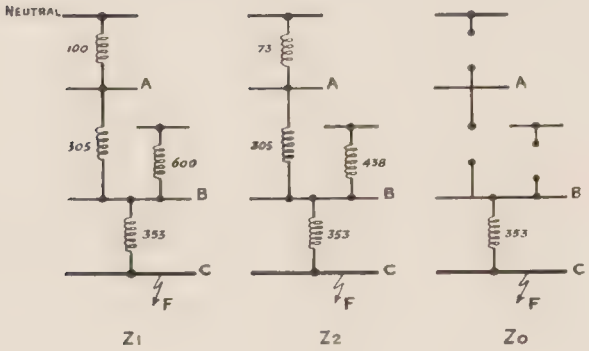


FIG. 13-49.

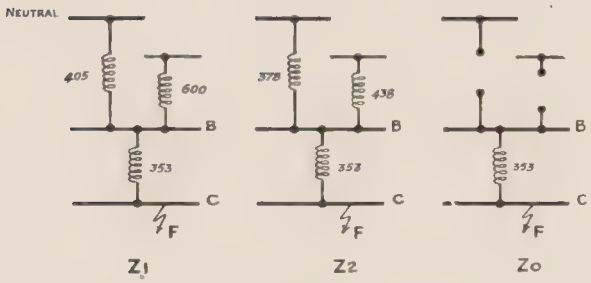


FIG. 13-50.

Had we to determine the fault current for a line to line fault, the formula would be

$$If = \frac{\sqrt{3} \times I \times 100}{Z_1 + Z_2}$$

or for a three-phase fault,

$$If = \frac{I \times 100}{Z_1}$$

In order to determine the distribution of current throughout the complete network, it is convenient to adopt a method suggested by Wagner

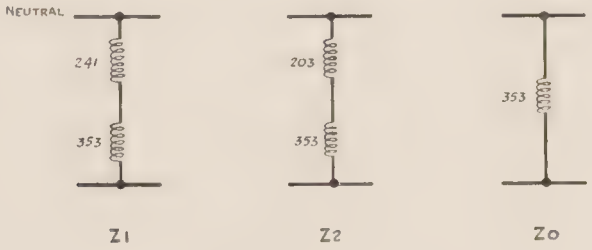


FIG. 13-51.

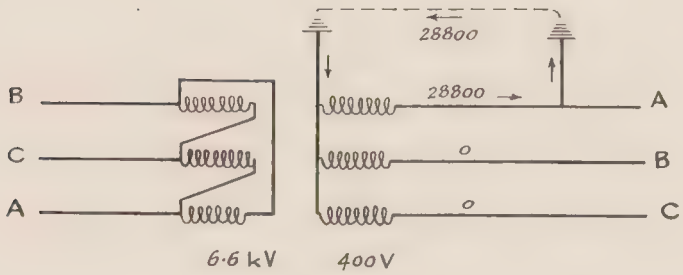
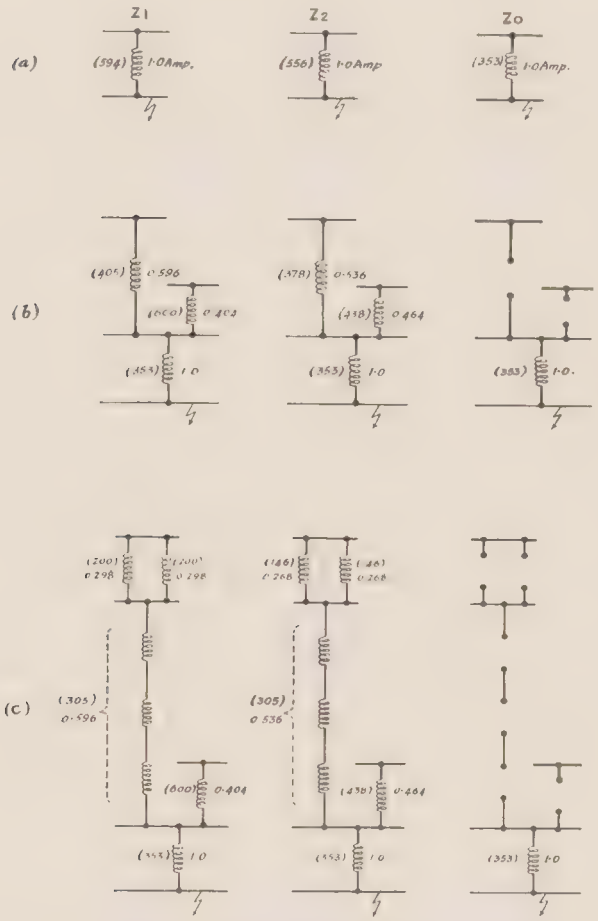


FIG. 13-52.

and Evans where the reactance diagrams (Figs. 13-48, 13-49, 13-50, 13-51) are worked through in a reverse order, and assuming a figure of one amp. at the fault determine the proportions of this in other branches of the network in inverse proportion to the reactances. The three sequences are placed side by side and Fig. 13-53 shows the stages of calculation. Figures in brackets are reactance values; the other figures being current values in terms of one ampere at the fault. At this stage, it will be noted that all values of current are in terms of the 400 volt star base voltage. Correction for voltage and star/delta transformation will be made later. We have seen (page 286) that the total fault current If can be split into its sequence values as follows :—

$$If_1 = If_2 = If_0 = If/3 = 28{,}800/3 = 9{,}600 \text{ amps.}$$

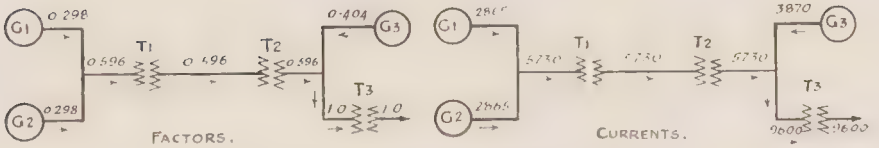
This value is then equal to our one amp. in Fig. 13-53 (*c*), and by using the factors throughout the remainder of the network we obtain the current distribution on the 400 volt base. This will be clear from Fig. 13-54, where, on the left, are shown the factors (taken from Fig. 13-53 (*c*)) and



NOTE.—FIGURES IN BRACKETS ARE REACTANCES.

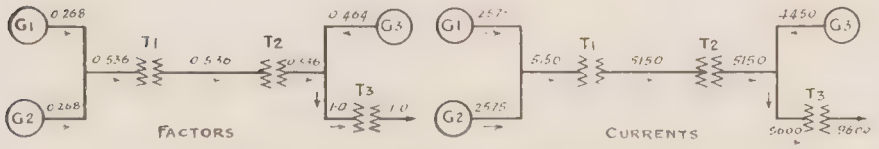
FIG. 13-53.

on the right the current values obtained by using these factors applied to the total current in each phase sequence, *i.e.*, 9,600 amps. These values are, of course, those in line A, the faulted line. Adding the values given in Fig. 13-54 for I_1, I_2 and I_0, we get the total currents in line A throughout the network, the result being Fig. 13-55. It remains now to determine values for lines B and C, and using formula previously given (page 286) we get,



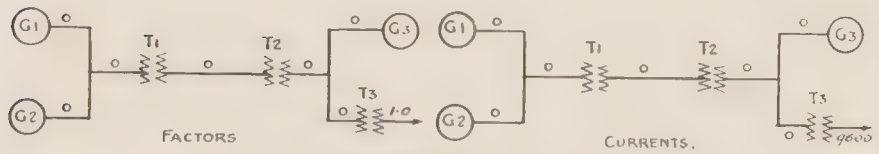
I_1 = POSITIVE PHASE SEQUENCE CURRENT—LINE A.

(*a*)



I_2 = NEGATIVE PHASE SEQUENCE CURRENT—LINE A.

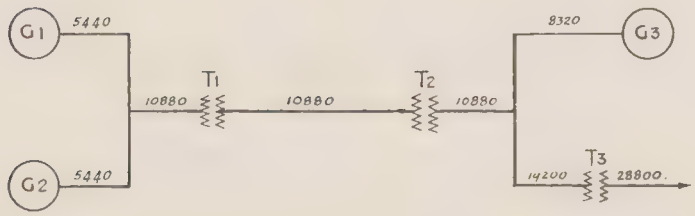
(*b*)



I_0 = ZERO PHASE SEQUENCE CURRENT—LINE A.

(*c*)

FIG. 13-54.



TOTAL FAULT CURRENTS IN LINE A ON 400 VOLT STAR BASE, AND BEING THE SUM OF THE VALUES $I_1 + I_2 + I_0$, FIG. 13-54.

FIG. 13-55.

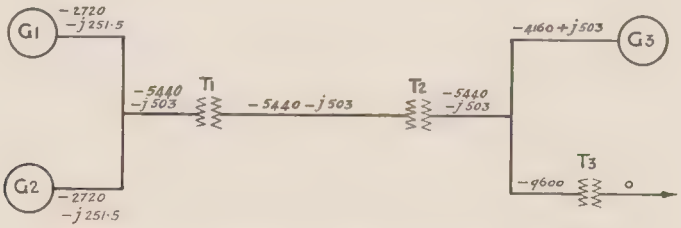
LINES B AND C (GENERATORS G1 AND G2).

$$\begin{aligned} I_B &= I_0 + a^2I_1 + aI_2 \\ &= I_0 + I_1 (-0{\cdot}5 - j0{\cdot}866) + I_2 (-0{\cdot}5 + j0{\cdot}866) \\ &= I_0 - 0{\cdot}5 (I_1 + I_2) - j0{\cdot}866 (I_1 - I_2) \\ &= 0 - 0{\cdot}5 (2{,}865 + 2{,}575) - j0{\cdot}866 (2{,}865 - 2{,}575) \\ &= -2{,}720 - j251{\cdot}5 \\ I_C &= I_0 + aI_1 + a^2I_2 \\ &= -2{,}720 + j251{\cdot}5 \end{aligned}$$

These are the values for *each* generator.

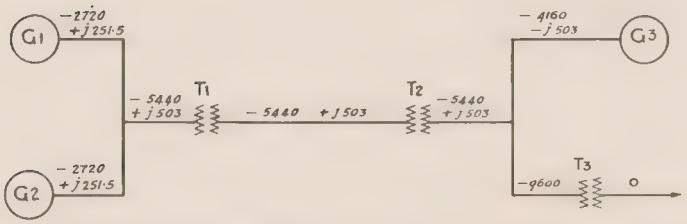
LINES B AND C (PRIMARY TRANSFORMER T1).

I_B and I_C here will be the addition of the values for the two generators G1 and G2.



TOTAL FAULT CURRENTS IN LINE B ON 400 VOLT STAR BASE.

FIG. 13-56.



TOTAL FAULT CURRENTS IN LINE C ON 400 VOLT STAR BASE.

FIG. 13-57.

LINES B AND C (SECONDARY TRANSFORMER T1 AND SECONDARY TRANSFORMER T2).

As we are still working on our common base, these values will be the same as for the primary of T1.

LINES B AND C (GENERATOR G3).

$$\begin{aligned} I_B &= I_0 + a^2I_1 + aI_2 \\ &= -4{,}160 + j503 \\ I_C &= I_0 + aI_1 + a^2I_2 \\ &= -4{,}160 - j503 \end{aligned}$$

LINES B AND C (PRIMARY TRANSFORMER T3).

The values here will be the addition of the secondary currents from T2 and the current from G3.

The values so obtained can now be set down as in Figs. 13-56, and 13-57 for Lines B and C respectively. It remains only to ascertain the

currents at the *actual* voltages, taking into account star/delta transformation, using the equations on page 287. Starting from the fault, and working backwards.

PRIMARY LINES T3.

$$\text{Line A} = -\frac{231}{6{,}600} \times (0-0) = 0 \text{ ampere.}$$

$$\text{Line B} = -\frac{231}{6{,}600} \times (0-28{,}800) = 1{,}010 \text{ amperes.}$$

$$\text{Line C} = -\frac{231}{6{,}600} \times (28{,}800-0) = -1{,}010 \text{ amperes.}$$

SECONDARY LINES T2 AND LINES G3.

The current in these lines is at the same voltage as the primary lines of T3. Therefore the values for the latter will be divided in the proportion 8,320/19,200 for the Generator G3 and 10,880/19,200 for T3. Thus,

$$\text{Line A } G3 = \frac{8{,}320}{19{,}200} \times 0 = 0 \text{ amperes.}$$

$$\text{Line B } G3 = \frac{8{,}230}{19{,}200} \times 1{,}010 = 438 \text{ amperes.}$$

$$\text{Line C } G3 = \frac{8{,}320}{19{,}200} \times -1{,}010 = -438 \text{ amperes.}$$

and by subtraction (G3 from T3) we get

SECONDARY LINES T2.

Line A = 0 amperes.
Line B = 1,010 — 438 = 572 amperes.
Line C = — 1,010 — (— 438) = — 572 amperes.

PRIMARY LINES T2, converting from secondary currents T2.

$$\text{Line A} = -\frac{3{,}810}{33{,}000} [572 - (-572)] = -132 \text{ amperes}$$

$$\text{Line B} = -\frac{3{,}810}{33{,}000} (-572 - 0) = 66 \text{ amperes.}$$

$$\text{Line C} = -\frac{3{,}810}{33{,}000} (0 - 572) = 66 \text{ amperes.}$$

PRIMARY LINES T1, converting from primary currents T2.

$$\text{Line A} = -\frac{19{,}050}{6{,}600} (66 - 66) = 0 \text{ amperes.}$$

$$\text{Line B} = -\frac{19{,}050}{6{,}600} [66 - (-132)] = -572 \text{ amperes.}$$

$$\text{Line C} = -\frac{19{,}050}{6{,}600} (-132 - 66) = 572 \text{ amperes.}$$

GENERATORS G1 AND G2.

The currents here will be one-half of those in the primary lines of T1 :—

Line A = 0 amperes.
Line B = —286 amperes.
Line C = 286 amperes.

We are now able to construct a diagram of the complete network to show the magnitude and direction of current at each point due to an earth fault at a point just beyond the transformer T3. The diagram is shown in Fig. 13-58.

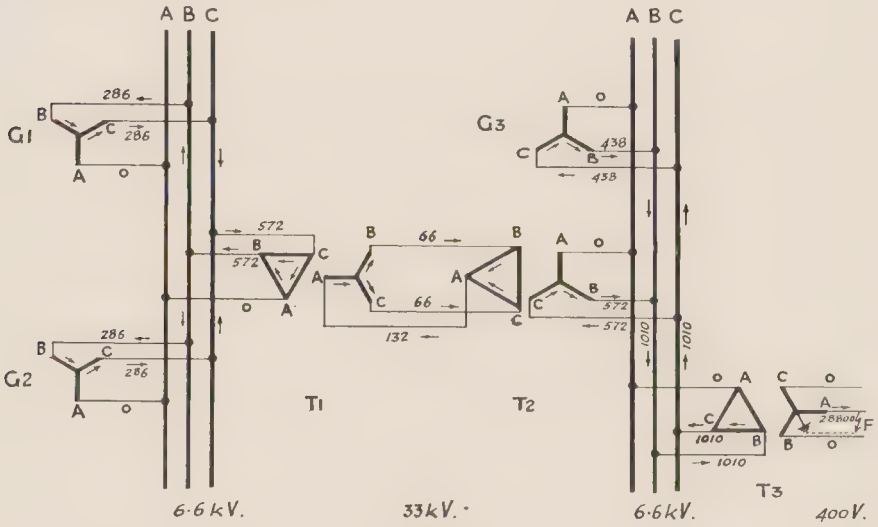


FIG. 13-58.

The calculations could, with equal facility, be carried out using ohmic values instead of percentage. In this case (and as previously indicated) a voltage base is chosen instead of a kVA base. Taking the example in Fig. 13-47, it is convenient to take as a base the voltage at the fault, *i.e.*, 400 volts and the following will indicate the procedure for calculating the fault current to earth.

G1 OR G2 (10,000 kVA 6·6 kV 20% REACTANCE).

F.L. Normal Current = 876 amperes.

$$\text{Reactance to Neutral} = j\frac{20}{100} \times \frac{3{,}810}{876} = j0{\cdot}87 \text{ ohms.}$$

Referred to 400 volt Star Base.

$$\text{Reactance to Neutral} = j0{\cdot}87 \left(\frac{231}{3{,}810}\right)^2 = j0{\cdot}0032 \text{ ohms.}$$

Thus, $Z_1 = j0{\cdot}0032$ ohms

$$Z_2 = 0{\cdot}73Z_1 = j0{\cdot}002335 \text{ ohms.}$$

T1 or T2 (5,000 kVA 6·8% reactance T1 at 6·6 kV, T2 at 33 kV).

F.L. Normal Current T1 = 438 amperes at 6·6 kV.

F.L. Normal Current T2 = 87.5 amperes at 33 kV.

$$\text{Reactance to Neutral T1} = j\frac{6\cdot8}{100} \times \frac{3{,}810}{438}$$

$$= j0\cdot592 \text{ ohms.}$$

$$\text{Reactance to Neutral T2} = j\frac{6\cdot8}{100} \times \frac{19{,}050}{87\cdot5}$$

$$= j14\cdot8 \text{ ohms.}$$

Referred to 400 volt Star Base.

$$T1 = j0\cdot592 \left(\frac{231}{3{,}810}\right)^2 = j0\cdot00218 \text{ ohms.}$$

$$T2 = j14\cdot8 \left(\frac{231}{19{,}050}\right)^2 = j0\cdot00218 \text{ ohms.}$$

Thus, $Z_1 = Z_2 = j0\cdot00218$ ohms for T1 or T2.

G3 (2,000 kVA 6·6 kV 12% reactance).

F.L. Normal Current = 175 amperes.

$$\text{Reactance to Neutral} = j\frac{12}{100} \times \frac{3{,}810}{175} = j2\cdot61 \text{ ohms.}$$

Referred to 400 volt Star Base

$$\text{Reactance to Neutral} = j2\cdot61 \left(\frac{231}{3{,}810}\right)^2 = j0.0096 \text{ ohms.}$$

Thus, $Z_1 = j0\cdot0096$ ohms

$Z_2 = 0\cdot73Z_1 = j0\cdot007$ ohms.

T3 (1,500 kVA 6·6 kV 5·3% reactance).

F.L. Normal Current = 131·3 amperes.

$$\text{Reactance to Neutral} = j\frac{5\cdot3}{100} \times \frac{3{,}810}{131\cdot3} = j1\cdot535 \text{ ohms.}$$

Referred to 400 volt Star base

$$\text{Reactance to Neutral} = j1\cdot535 \left(\frac{231}{3{,}810}\right)^2 = j0\cdot00565 \text{ ohms.}$$

Thus $Z_1 = Z_2 = Z_0 = j0\cdot00565$ ohms.

Overhead Line (33 kV).

Reactance to Neutral = $j3\cdot6$ ohms.

Referred to 400 volt Star base.

$$\text{Reactance to Neutral} = j3\cdot6 \left(\frac{231}{19{,}050}\right)^2 = j0\cdot00053 \text{ ohms.}$$

Thus $Z_1 = Z_2 = j0\cdot00053$ ohms.

Proceeding now as described earlier, a series of network reduction diagrams will result in the ascertainment of a single equivalent reactance for each of the phase sequences.

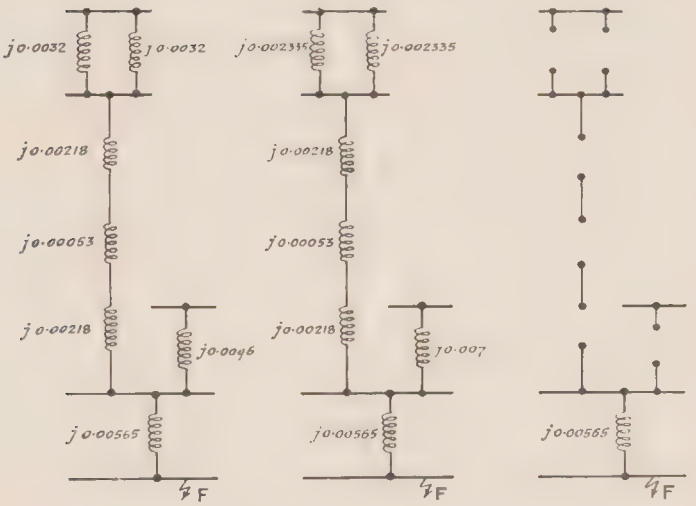


FIG. 13-59.

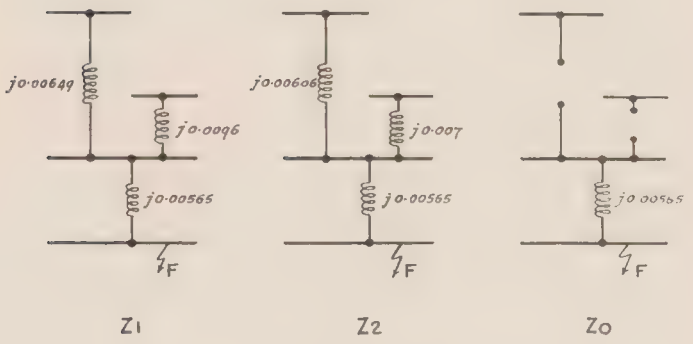


FIG. 13-60.

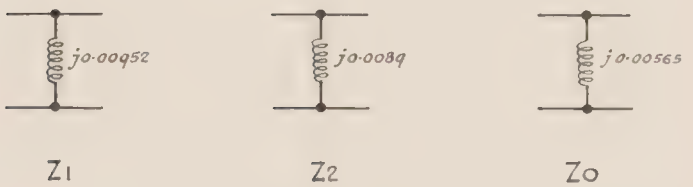


FIG. 13-61.

These diagrams are given in Figs. 13-59, 13-60 and 13-61.
We now have :—

$$Zt = Z_1 + Z_2 + Z_0$$
$$= j0{\cdot}00952 + j0{\cdot}0089 + j{\cdot}000565$$
$$= j0{\cdot}02407 \text{ ohms.}$$

The total earth fault current is then :—

$$If = \frac{3\,E}{Zt} = \frac{3 \times 231}{0{\cdot}02407} = 28{,}800 \text{ amperes.}$$

exactly as calculated by the percentage reactance method. Current distribution calculation will be as before.

It is of interest here to note that where there are two reactances in parallel, current distribution is determined as follows :—

$$I_A = \frac{ZY}{ZX + ZY} \times It$$

$$I_B = \frac{ZX}{ZX + ZY} \times It$$

where Fig. 13-62 represents the conditions.

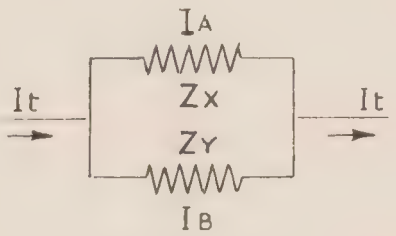


Fig. 13-62.

Where, as previously demonstrated, a delta/star conversion is undertaken, it is necessary when determining current distribution in the network to work backwards. For example, the reactance reduction procedure might be as shown at Fig. 13-63 where a delta/star conversion occurs from (*a*) to (*b*).

Working backwards for current distribution we have Fig. 13-64, working from (*e*) to (*a*) and at (*b*) we have currents in a star to be converted to distribution in the delta network at (*a*). This conversion is carried out by making use of the fact that the voltage difference between any two terminals of the delta group is the voltage difference between the two corresponding terminals of the star group. These voltage differences may be determined from the current distribution and reactances of the star group. Having found the voltage difference it is divided by the corresponding delta impedance, giving the current distribution in the equivalent branch of the delta group. Fig. 13-65 illustrates this where at (1) we have

the delta/star conversion of reactances and at (2) the star/delta conversion for current distribution, the latter determined as follows :—

Voltage Difference A to F (Fig. 13-65)

$$= (1{\cdot}0 \times j2{\cdot}33) + (0{\cdot}504 \times j1{\cdot}66) = j3{\cdot}167 \text{ volts.}$$

Current Distribution

$$= \frac{j3{\cdot}167}{j6} = 0{\cdot}528 \text{ amperes.}$$

The other two branches of the delta may be similarly calculated.

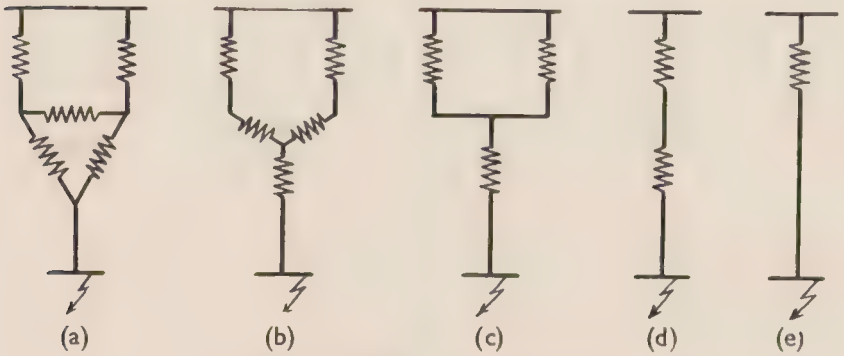


FIG. 13-63.

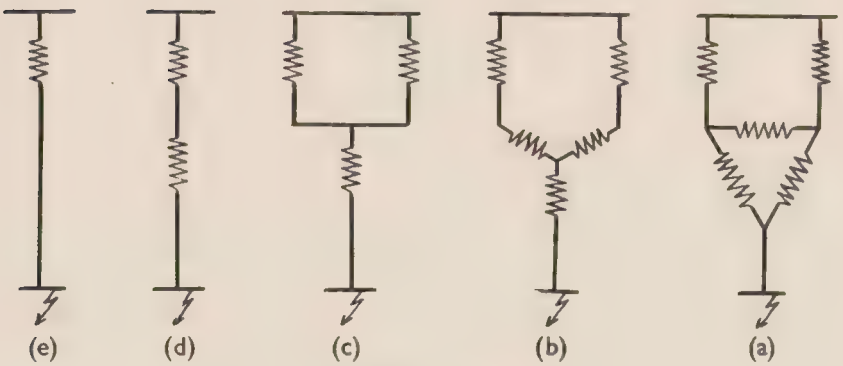


FIG. 13-64.

SHORT-CIRCUIT STRESSES.

Having considered the methods of calculating short-circuit currents in an electrical network, it is appropriate now to consider the stresses caused in busbar and connection runs.

When currents flow in two parallel conductors, there is a mechanical force between the conductors—of attraction when the currents are in the

same direction and of repulsion when the currents are in opposite directions. When carrying normal current, these forces are negligible but under short-circuit conditions they can be appreciable and it is necessary to ensure that the busbar and connection supports can withstand them, even though of momentary duration.

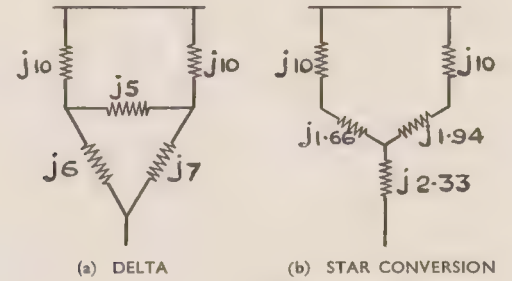


FIG. 13-65.

The force between busbars or other long conductors may be calculated as follows.

If I be the d.c. value of current or the r.m.s. value of an alternating current, then,

$$F = \frac{4{\cdot}5 \times I^2 \times l}{10^8 \times S}$$

where F = Force in lbs.
l = length of conductor in inches.
S = Spacing between conductors (centres) in inches.

In the a.c. case, a symmetrical and sinusoidal current wave is assumed. The formula may be converted to lbs. per foot run, and becomes,

$$F = \frac{5{\cdot}4 \times I^2}{10^7 \times S} \text{ lbs. per foot run.}$$

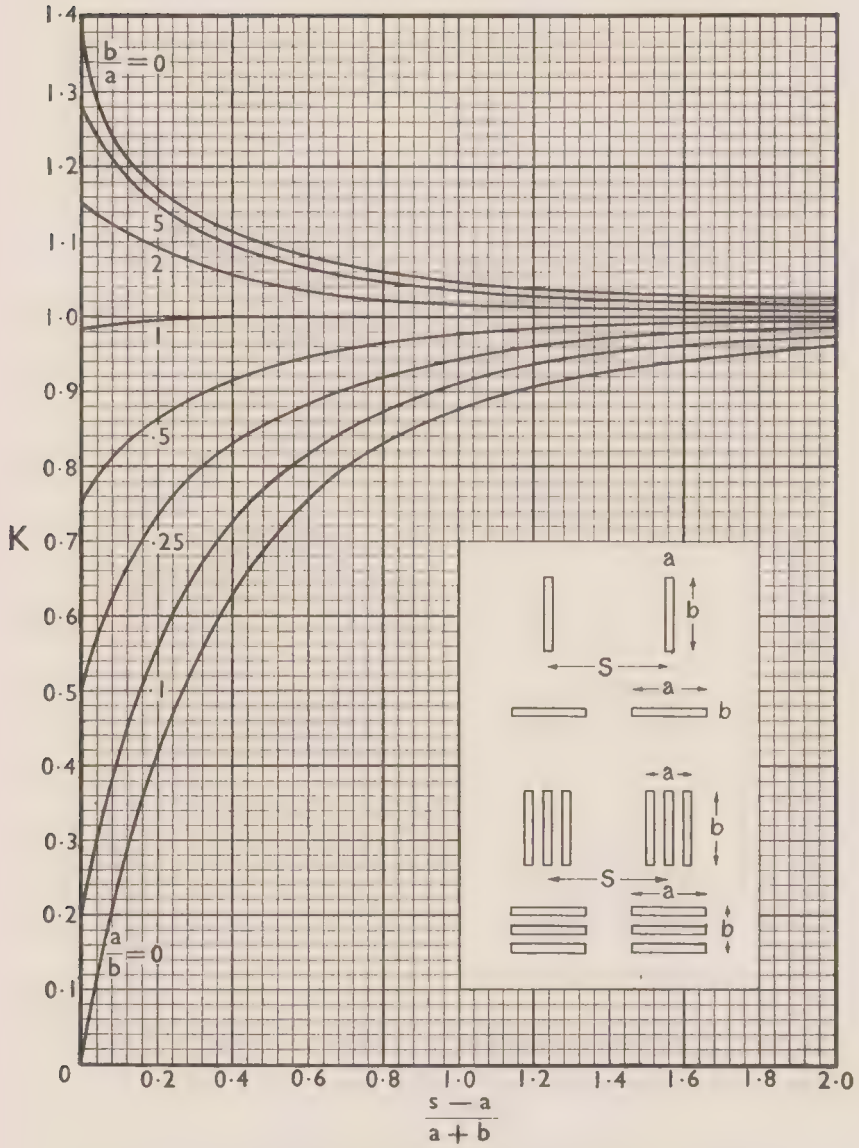


FIG. 13-66.—*Shape Factor for rectangular copper conductors (The Copper Development Association).*

For a maximum value of F, the peak current must be used, *i.e.*, $\sqrt{2}$ times the r.m.s. value and then

$$F = \frac{5{\cdot}4 \times (\sqrt{2}\ I\ \text{r.m.s.})^2}{10^7 \times S} \text{ lbs. per foot run.}$$

$$\text{or } \frac{10{\cdot}8 \times I\ \text{r.m.s.}^2}{10^7 \times S} \text{ lbs. per foot run.}$$

It has been shown earlier that under short-circuit conditions at least one phase will be asymmetrical, and that the peak value of current in a fully asymmetrical current wave may be $1{\cdot}414 \times 1{\cdot}8 = 2{\cdot}55$ times the r.m.s. value of the symmetrical value. As this is the condition against which busbar and conductor supports must be proof, it is usual to calculate the forces on this basis, and the formula becomes,

$$F = \frac{5{\cdot}4 \times (1{\cdot}414 \times 1{\cdot}8 \times I\ \text{r.m.s.})^2}{10^7 \times S}$$

$$= \frac{35{\cdot}12 \times I\ \text{r.m.s.}^2}{10^7 \times S} \text{ lbs. per foot run.}$$

The foregoing is applicable generally to circular conductors. The majority of arrangements will be those of flat rectangular conductors and for these, a correction factor K is introduced into the formulæ, thus,

$$F = \frac{35{\cdot}12 \times I\ \text{r.m.s.}^2 \times K}{10^7 \times S}$$

K may be obtained from Fig. 13-66 by first determining the ratio,

$$\frac{s - a}{a + b}$$

where a = width of bar or bars.
b = depth of bar.
s = spacing between conductor centres.

After which K may be read directly from the curve for the ratio a/b. K for circular conductors is unity.

The formulæ so far given apply to long lengths only. For parallel conductors of short length, a particularly good example of which is that of circuit-breaker stems, modifications are required. Other problems of short-circuit forces on conductors are those concerning right-angle formations, and circuit-breaker cross-bars. These are dealt with fully in several of the works referred to in the Bibliography, particularly the "Switchgear Handbook," and "Calculation and Design of Electrical Apparatus."

BIBLIOGRAPHY.

*Calculation of Fault Currents in Electrical Networks**, R. T. Lythall (Pitman and Sons).

"NOTES ON THE CALCULATION OF NETWORK SHORT-CIRCUITS," G. J. O. Garrard, "G.E.C. Journal," February, 1937.

"ALTERNATOR REACTANCES," G. J. O. Garrard, "Electrician," August 5, 1939.

"CALCULATION OF INITIAL SYMMETRICAL SHORT-CIRCUIT CURRENTS FOR THE SELECTION OF CIRCUIT-BREAKERS," G. Cluley, "Metropolitan-Vickers Gazette," January, 1938.

Calculation of Network Short-Circuits, A. Garnett, The Draughtsman Publishing Co., Ltd.

"SHORT-CIRCUIT CALCULATIONS," M. G. Say, "Electrical Engineer," August 12, 1938.

"CALCULATING FAULT CURRENTS," G. J. O. Garrard, "The Electrical Review," Sept. 12, 1937.

"REACTANCE DROP OVER STRAP CONDUCTORS," G. E. Gittins, "The Metropolitan-Vickers Gazette," January, 1922.

"CALCULATION OF INDUCTANCE AND CURRENT DISTRIBUTION IN L.V. CONNECTIONS TO ELECTRIC FURNACES," C. C. Levy, Paper presented to Summer Convention, A.I.E.E., June, 1932.

Bulletin 169, American Bureau of Standards.

The Calculation and Measurement of Inductance and Capacitance, W. H. Nottage (Wireless Press, Ltd.).

"ENGINEERING CALCULATION OF INDUCTANCE AND REACTANCE FOR RECTANGULAR BAR CONDUCTORS," O. R. Schurig, "G. E. Review," May, 1933.

*The Calculation of Unsymmetrical Short-Circuits**, H. Rissik (Pitman and Sons).

"THE METHOD OF SYMMETRICAL CO-ORDINATES APPLIED TO THE SOLUTION OF POLYPHASE NETWORKS," C. Le G. Fortescue, "Transactions A.I.E.E.," 1918, Vol. 37.

Elements of Symmetrical Component Theory, G. W. Stubbings (Pitman and Sons).

Relay Systems, I. T. Monseth and P. H. Robinson (McGraw, Hill Publishing Co.).

Symmetrical Components as applied to the Analysis of Unbalanced Electrical Circuits, C. F. Wagner and R. D. Evans (McGraw, Hill Publishing Co.).

Vectorial Solution of A.C. Circuits, A. Garnett (The Draughtsman Publishing Co., Ltd.).

**Companion Volumes.*

" Earth Faults—Analysis by Method of Phase Sequence Components," G. A. Robertson, " Electrician," July 20, 1934 to May 10, 1935.

The J. & P. Transformer Book, S. Austen Stigant and H. Lacey (Johnson and Phillips, Ltd.).

Circuit Analysis of A.C. Power Systems, Vol. I, Edith Clarke (John Wiley and Sons).

" Decrement Curves for Power Systems," G. F. Dalziel, " Trans. A.I.E.E.," 1934, Vol. 53.

The Switchgear Handbook, Vol. II, W. A. Coates and H. Pearce (Pitman and Sons).

" The Management of Protective Gear on Power Supply Systems," W. Casson and F. H. Birch, " Journal I.E.E.," Vol. 89, Part II, No. 10, August, 1942.

" Evaluation of Fault Currents and Voltages," J. R. Mortlock, " B.T.H. Activities," April, 1941 and July, 1941.

" Short Circuit Conditions on Large Industrial l.v. Distribution Networks," T. S. G. Seaward, " Journal I.E.E.," Part I, Vol. 88, No. 3, March, 1941.

Calculation and Design of Electrical Apparatus, W. Wilson (Chapman and Hall).

Copper for Busbars, The Copper Development Association, Publication No. 22.

" Forces on Conductors during Short-Circuit," W. R. Tripp, " The Electric Journal," December, 1937.

" Electromagnetic Forces set up between Current-carrying Conductors during Short-Circuit," G. L. E. Metz, " Journal I.E.E.," Vol. 75, No. 454, October, 1934.

" Design of Switch Station Equipment," F. G. Sublet, " Electrical Engineer and Merchandiser " (Tait Publishing Co., Melbourne and Sydney).

CHAPTER XIV

CIRCUIT-BREAKER OPERATING MECHANISMS

MANY forms of operating mechanism have been used for the purpose of closing and opening an oil circuit-breaker, but the large majority are those which may be designated hand, spring, or solenoid. Other forms include motor, hydraulic, pneumatic, but our purpose will be served if these are regarded as outside the scope of the present chapter.

In the three more popular types, toggle leverages are generally employed, where levers are arranged to pass over dead centre, thus holding the circuit-breaker in its closed position. To open, the toggle is upset by pushing it back over the dead centre.

The amount by which the toggle passes dead centre need only be very small. This permits adequate support in the closed position, and yet provides a linkage which can readily be upset on demand. In the case of small mechanisms, a single toggle will suffice, but in the larger types for heavy duty circuit-breakers, toggles in series are not infrequent.

As an alternative to dead-centre toggle levers, a latch may retain the mechanism stable; to trip, the latch must be upset. In this case, the latch itself may be the toggle lever, latching over dead centre. In all operating mechanisms, two parts are easily recognisable (*a*) the assemblage of levers, links and trip devices at the closing device proper and (*b*) the levers and lift arms at the circuit-breaker arranged to impart the parallel motion necessary to close the circuit-breaker contact bars. Between these two parts there will be a link moving axially. This, in some designs, is arranged "pull to close" while in others, it may be "push to close." The latter has many advantages, particularly where making-current releases are fitted, where a quick reversal of motion is essential. Handles of both types are shown in Fig. 14-1.

HAND CLOSING.

This form of closing mechanism is the most economical of all forms. An external handle moving through an angle convenient to an operator is used to move the lever assembly and to close the circuit-breaker against its throw-off springs and the resistance due to contact pressure. The heaviest force is at the end of the closing stroke and it is an essential of hand closing mechanisms that the external handle should finish its travel at a position where an operator can exert maximum force. Reference back to Fig. 4-12 will illustrate a typical mechanism of the type described, in which the shape and final position of the external handle has been carefully studied to provide the features mentioned above.

Unfortunately, the hand closing mechanism introduces an element of risk which cannot be avoided. Quite obviously, the speed of closing is entirely in the hands of the operator, and he is free to hesitate at any point in the closing stroke. If hesitation occurs at the instant of contact make, severe arcing may lead to damage in the circuit-breaker and possibly to endangering the operator himself. To avoid this possibility, many mechanisms have what is described as a reverse action trip. This is more

usual in the small industrial class of circuit-breaker similar to those illustrated in Chapter VI, and the device in this class is of real service because of the usual simplicity of the mechanism and the relatively short closing lever provided, features which are forced on designers by considerations of cost. The reverse action trip operates to trip the circuit-breaker on the slightest backward movement of the handle.

It has been emphasised elsewhere that one of the most severe duties which a circuit-breaker may be called upon to perform is that of closing on to an existing short-circuit. In this event, high values of peak current occur at the instant of contact make and very considerable electromagnetic

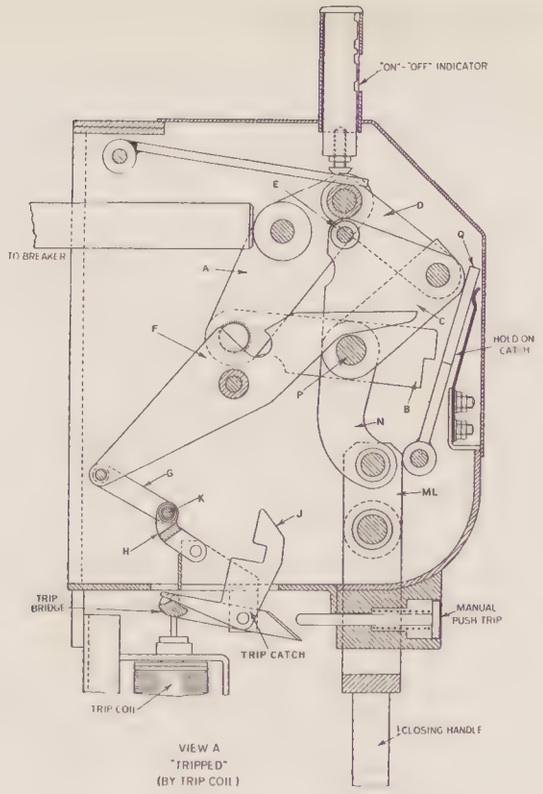
FIG. 14-2.—*Spring Closing Device, showing springs being charged.*

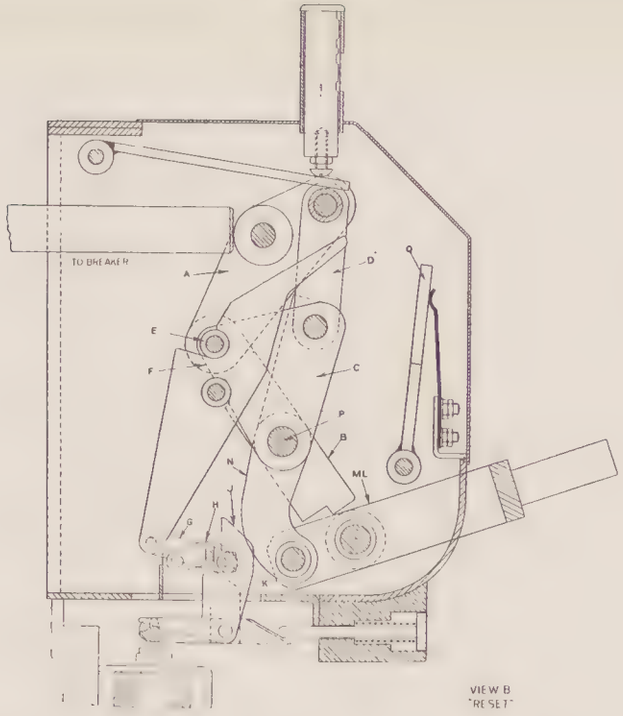
repulsion of the moving contacts arises. This repulsion increases as the square of the short-circuit current, and it can easily be that no operator, strong as he may be, can close a circuit-breaker home to the latched-in position against these forces with a hand closing mechanism. This may happen in spite of the trip-free mechanism as this may be delayed due to time limit fuses, or other forms of time lag. For reasons such as these, hand closing should be restricted to circuit-breakers where the breaking capacity does not exceed 150 MVA or not over 10,000 amperes breaking current. This recommendation is taken from B.S. 116.

In order to overcome the limitations of hand closing mechanism as described, and to ensure the safety of operators, devices have been evolved which are defined in B.S. 116 and B.S. 936 as "making-current releases." These will be described later, but when they are not, or cannot, be fitted, power closing mechanisms should be used.

SPRING CLOSING.

Because of the relatively high cost of installing the essential battery,





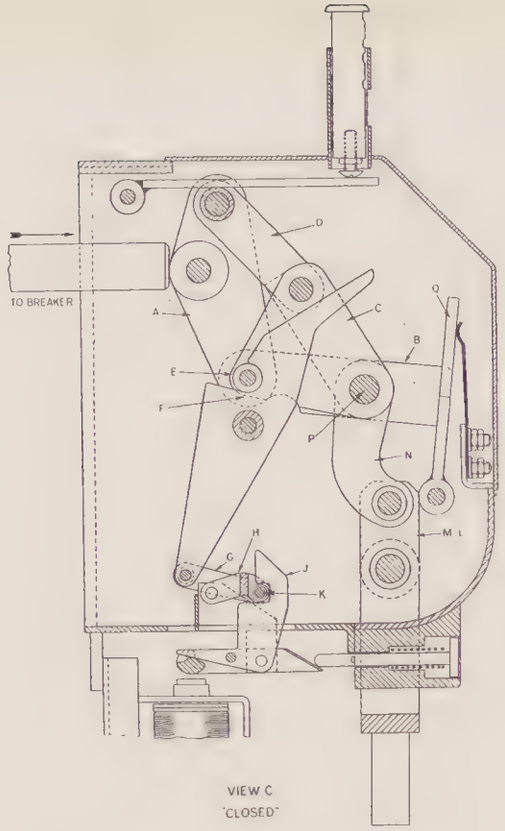
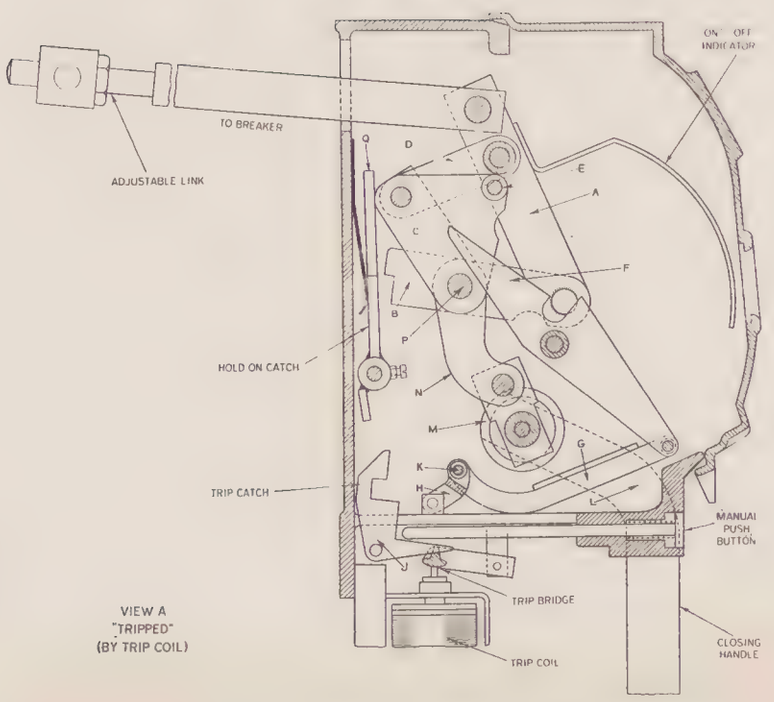
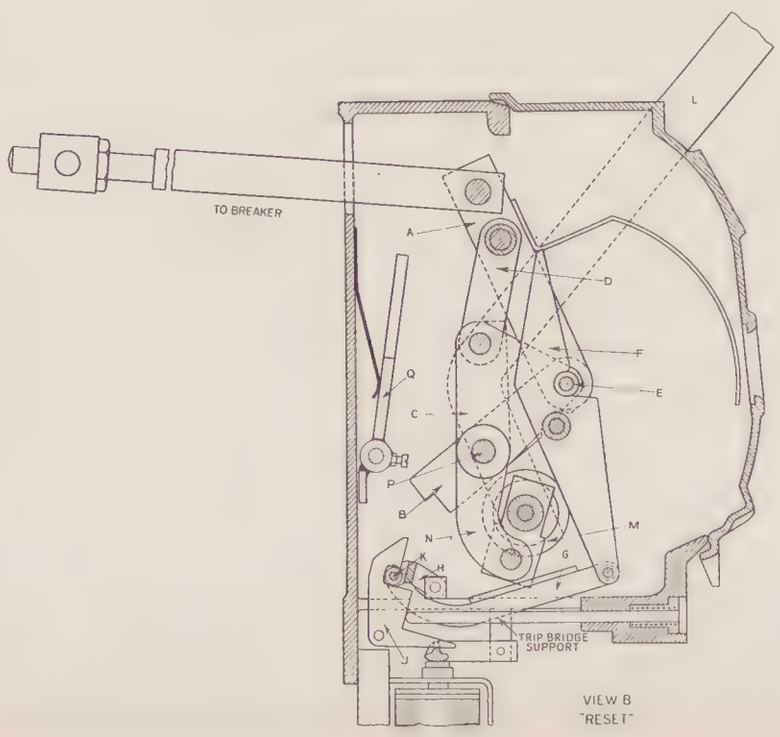
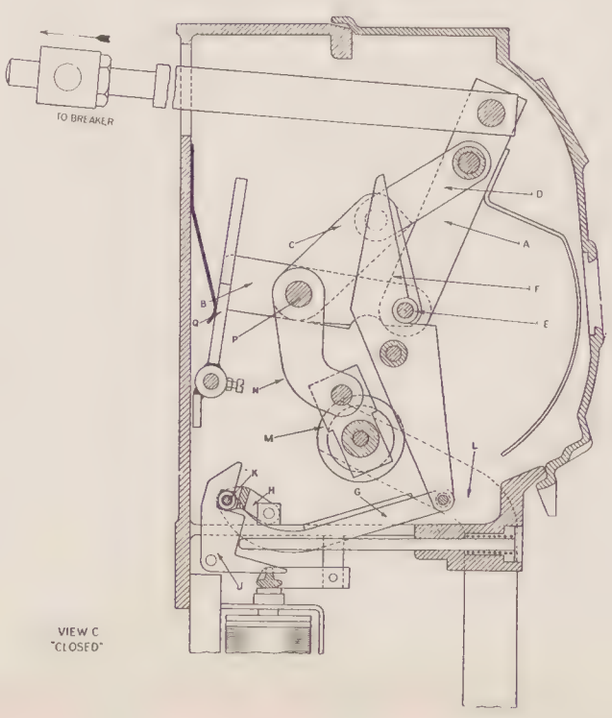


FIG. 14-1.—*Showing (above) the "push to close" type of operating mechanism and (below) the "pull to close" type.*







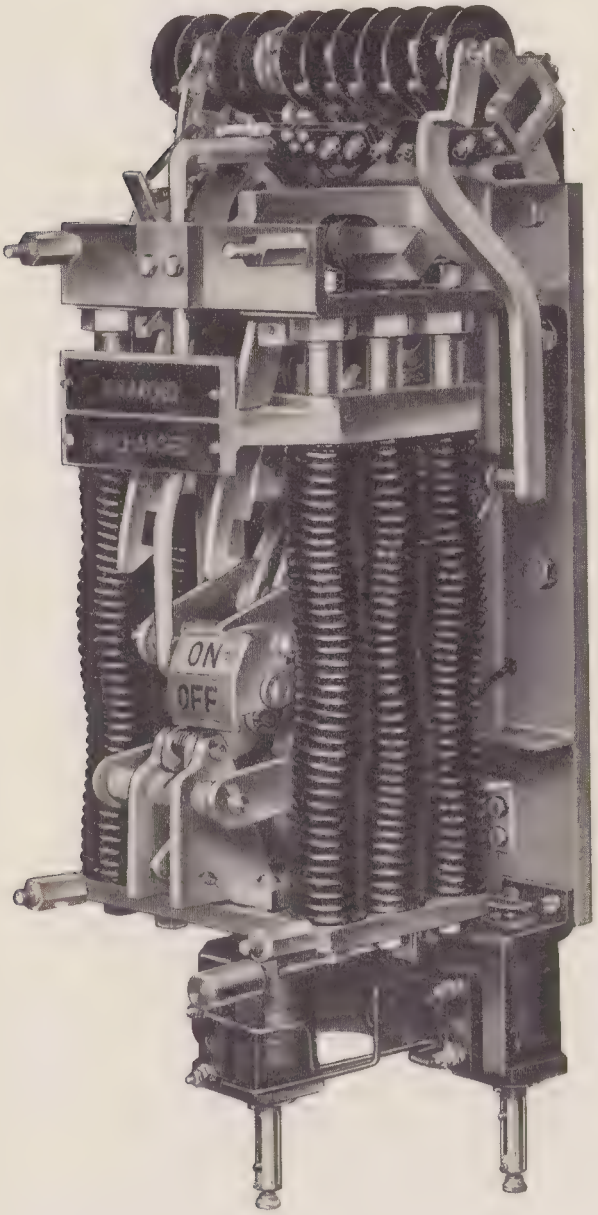


FIG. 14-3.—*Spring Closing Device (with cover removed).*

with its attendant charging equipment, so necessary for electrical closing devices, *e.g.*, solenoid, much work has been done in making available the spring closing device. In this, pre-compressed springs are used to close the circuit-breaker. In the devices provided to close relatively small circuit-breakers, manual loading of the springs is usual, in some designs by means of a handwheel geared to the spring, or, as in the type shown in Fig. 14-2, by means of two charging handles which, incidentally, are removed after the operation. In the fully compressed position, the springs are retained by a catch until such time as a closing operation is necessary, when release of the catch releases the springs to close the circuit-breaker. To release the catch, several methods are available, namely, by direct release by push knob, by lanyard at a small distance, or electrically by means of a small d.c. trip coil. In order of safety to the operator, the latter form of release gives maximum protection.

Many devices of this type exist in which one large sprnig is used. In others there is one large spring concentric with a smaller spring, the latter being wound opposite hand to the large spring to avoid fouling. Yet a further design uses a number of smaller springs, and one such device using six springs is shown in Fig. 14-3. For this it is claimed that breakage or fatigue of one spring will not affect the efficient operation of the mechanism. This illustration shows the springs in the charged (compressed) state and it will be noted that the amount of compression is quite small.

The spring closing device is superior to hand closing where a making-current release cannot be fitted because, once initiated, the closing stroke must be completed irrespective of the operator. Even so, spring closing is not easy. This is because contrary to the requirements of successful circuit-breaking closing, maximum effort is exerted at the *beginning* of the stroke, *i.e.*, at a time when the closing effort necessary is minimum. This is opposite to the effort exerted by the electrical solenoid and is illustrated in Fig. 14-4. For this reason, ample energy must be stored in the springs. This leads to a device which is very severe on the linkages when closing under normal load conditions, so that here again relief is sought by fitting the making-current release.

Solenoid Closing.

The d.c. solenoid, providing its cost can be justified, is the ideal operating mechanism and offers the designer the ideal stroke/pull characteristics, in that they line up with those so necessary in circuit-breaker closing, as has been indicated above and in Fig. 14-4. The solenoid is short-time rated, being cut out of circuit after having completed its closing operation. Nevertheless, several reclosures in rapid succession may be necessary and the design must take this into account. The supply to the solenoid coil is controlled by a contactor equal to the duty of switching in and out an inductive circuit which may represent a load up to 50 kW for the largest solenoid. To provide this supply, a battery is usually installed together with charging equipment. To allow for a failure of supply, means are provided to close the circuit breaker by hand.

The attribute of giving maximum power at the end of the stroke when it is most needed leads to difficulties as the moving system must come to rest and do so without damaging the breaker or solenoid. To this end spring or oil dashpot buffers can be fitted to absorb energy at the end of the stroke.

A typical solenoid is shown in Fig. 14-5.

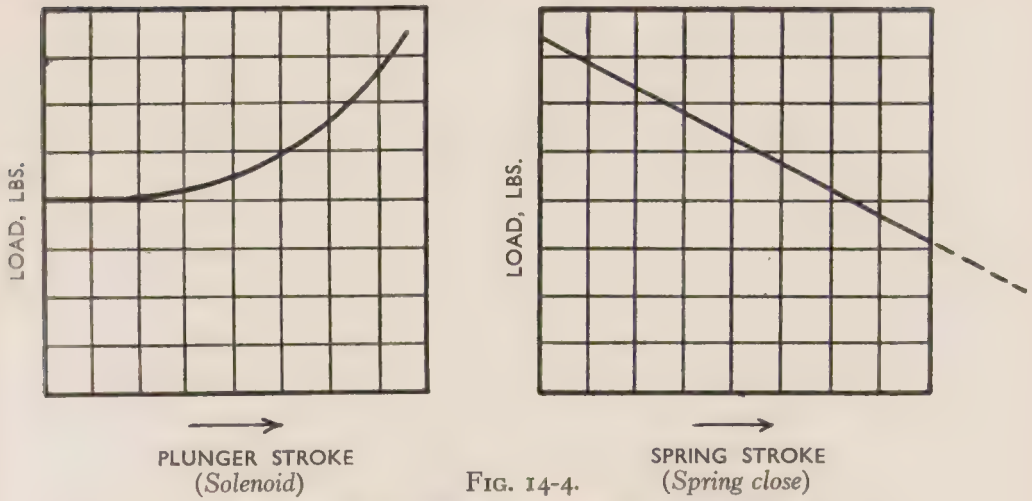


FIG. 14-4.

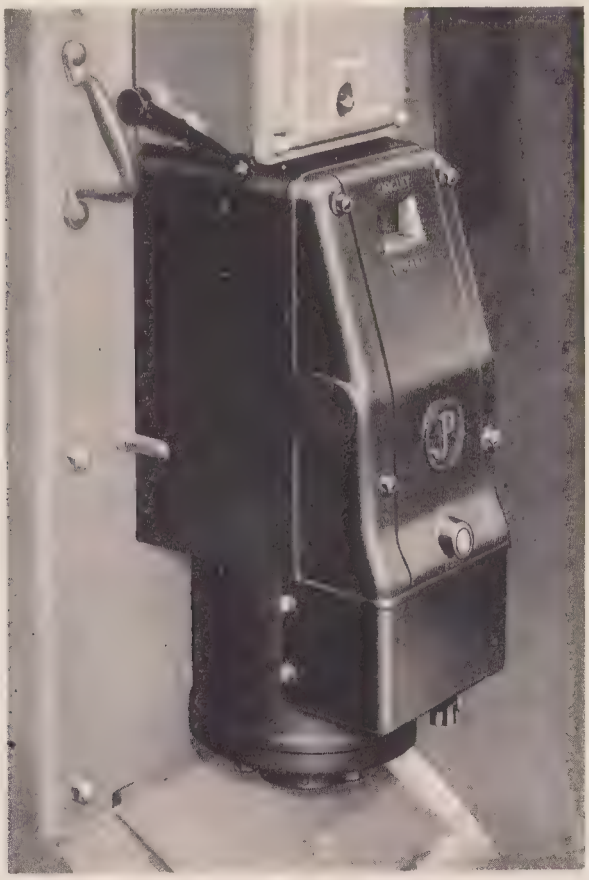


FIG. 14-5.—*Solenoid Operating Mechanism.*

MAKING-CURRENT RELEASE.

B.S. 116 and B.S. 936 define a making-current release as a device " which, during a closing operation, causes a trip-free circuit-breaker to open automatically and without intentional time delay when the making current exceeds a predetermined value." Such devices have been designated, alternatively, " force trips," " inertia trips," or " momentum trips."

The whole purpose of the device is to safeguard an operator and/or the circuit-breaker when closing on to an existing short-circuit. It is well-known that this condition involves heavy currents, in the worst case approximately 2·55 times the r.m.s. value of breaking current. Thus, at 250 MVA, 6·6 kV, the breaking current is 22,000 amperes, and the making current may reach 56,000 amperes. Such values of current lead to considerable electromagnetic forces tending to stop the closing operation.

If hesitancy occurs, or the operator hovers at the contacts, there is grave danger that the circuit-breaker will suffer damage, and this may involve the operator. If, then, a circuit-breaker cannot be closed right and home latched closed until released by the protective devices, it is desirable that some device be provided which will, at the slightest hesitancy,

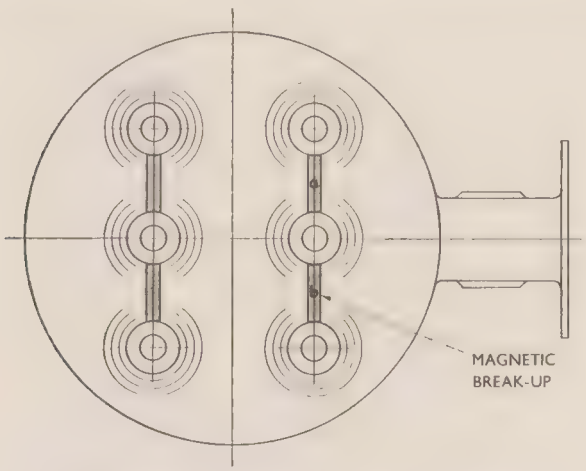


FIG. 14-6.—*Break-up of magnetic circuit in breaker top frame.*

upset the operating mechanism, so that the circuit-breaker is free to open immediately, and cannot be held against opening.

This is what the making-current release sets out to do. It appears in several forms, some mechanical, some electrical. In the former, energy is imparted to a movable mass during the first part of the closing operation. The momentum of this mass is such as to cause tripping if there is any slowing up on the part of the mechanism imparting energy to it. Unlike electrical devices, it can function at any point in the closing stroke. In electrical types, reference is made to the value of current and therefore the arcing contacts must touch before the device becomes effective.

One device recently evolved (Patent No. 553105) uses the break-up of the magnetic circuit in the circuit-breaker top plate, which has been the practice for many years, as the basis of a making-current release.

Fig. 14-6 illustrates how this break-up has been achieved by the insertion of non-magnetic strips between the phase conductor bushings.

Normally, this break-up is only essential for normal currents of 600 or 800 amperes and above, and originally its purpose was to eliminate local heating in the top plate. In order to utilise the making-current release, all top plates irrespective of normal current must be so arranged.

Two soft iron armatures are arranged to lie immediately above, but clear of, the gaps in the frame (*a* and *b* in Fig. 14-6) and are hinged to a spindle carried in bearing brackets supported on the top plate, as shown in Fig. 14-7. From this spindle, a lever is arranged and coupled by a Bowden wire or other means to the trip catch of the closing mechanism. Up to predetermined values of current, the two armatures lie at an angle to the top plate to leave a gap between them and the plate. If, during closing, the current exceeds the value for which the device is set, the armatures are attracted to the top plate in the manner of all electromagnets, and in moving, trip the circuit-breaker.

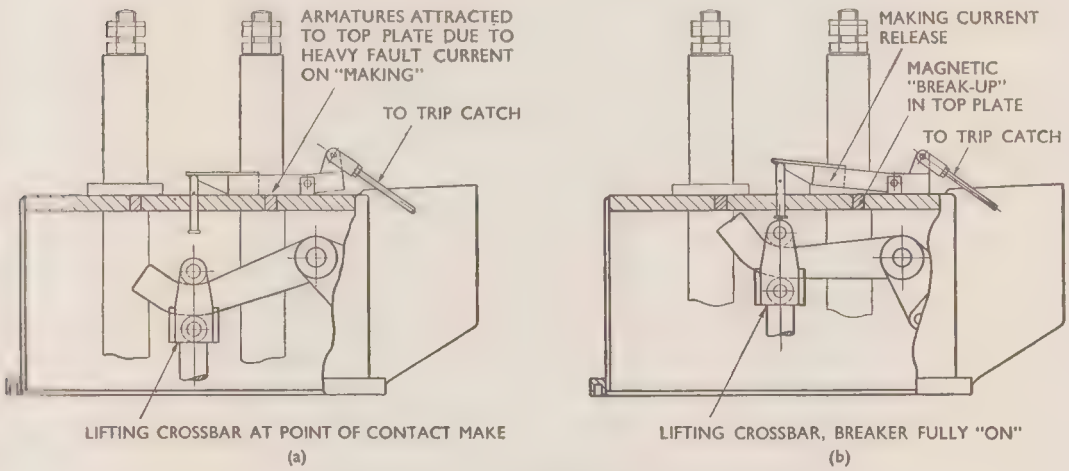

ARMATURES ATTRACTED TO TOP PLATE DUE TO HEAVY FAULT CURRENT ON "MAKING"
TO TRIP CATCH
LIFTING CROSSBAR AT POINT OF CONTACT MAKE
(a)
MAKING CURRENT RELEASE
MAGNETIC "BREAK-UP" IN TOP PLATE
TO TRIP CATCH
LIFTING CROSSBAR, BREAKER FULLY "ON"
(b)

Fig. 14-7.—*Making-current release fitted to circuit-breaker.*

This type of release can be set to operate at a value of current well *below* the maximum peak fault current. Bearing in mind the recommendations of B.S. 116 that when the fault current exceeds 10,000 amperes some form of power closing device be used, this value of current is used as the setting for the making-current release. At this setting it is possible that an operator may be able to fully close the circuit-breaker against fault currents of this magnitude. If he can he will operate at such a speed that he will beat the making-current release and latch in, leaving the normal protective gear to trip the breaker in its own time. If he fails, then the release will safeguard the operator.

Under normal conditions of closing, or when the fault current is so low as not to impede the closing stroke, the circuit-breaker mechanism is latched closed, and in latching in renders the making-current release inoperative. This occurs at the very last moment in order to retain the benefit of the release until it is certain that the operator can latch the breaker in.

This feature is essential too, to ensure that the device does not act as an overcurrent release to the exclusion of the protective devices purposely installed. This lock-out feature is shown at (*b*) in Fig. 14-7.

In the mechanical forms of making-current release, there is a possibility that it will function due to contact burns slowing up a closing stroke. This condition does not arise with electrical devices.

A making-current release of the magnetic type as described is shown fitted to a circuit-breaker in Fig. 14-8.

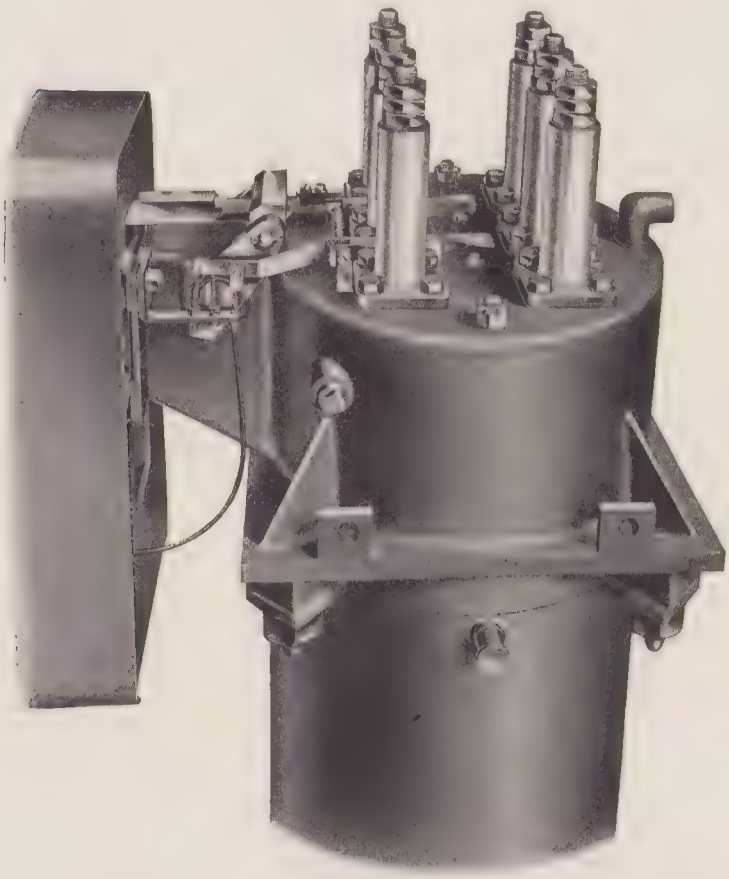


FIG. 14-8.—*Showing Making-current Release on circuit-breaker top plate.*

TRIPPING DEVICES.

In all forms of operating mechanism, it must be possible to fit the usual array of trip coils. These include overload, earth fault, shunt and under-voltage.

These usually appear below the handle and normal practice is to fit time limit fuses at this point on overload trips, thus avoiding leads between

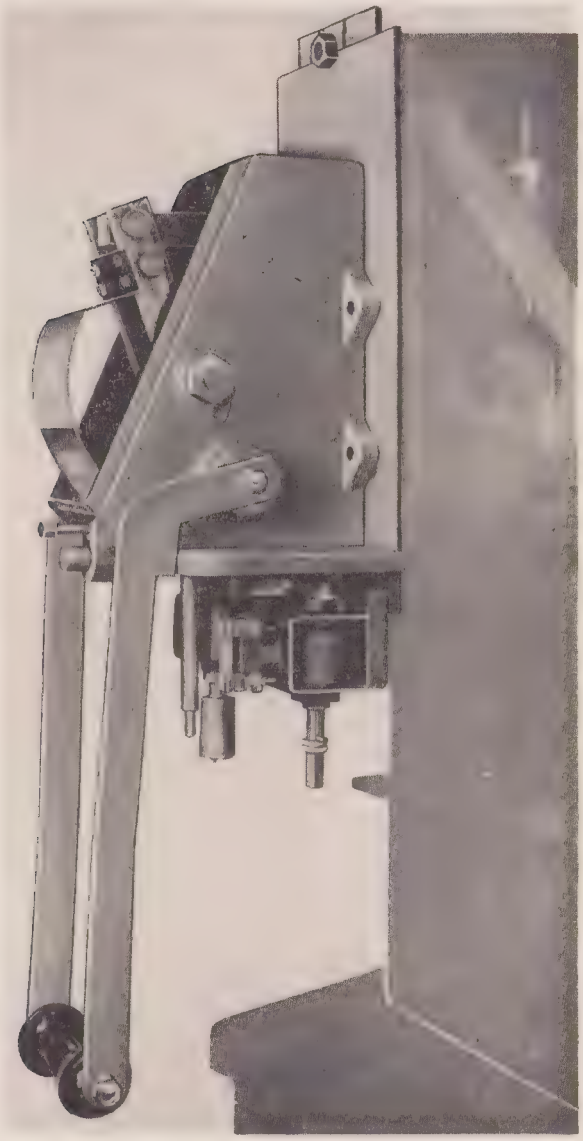


FIG. 14-9.—*Hand Operating Mechanism, showing trip coils and time limit fuses.*

coil and fuse. A typical arrangement is shown in Fig. 14-9, where the cover has been removed to show the trip coils.

Auxiliary Supplies.

For giving supply to shunt trip coils, a 30 volt battery is used and a typical equipment is described in Chapter XXVI. This is perferable to using a.c. derived from the system itself as this may be lost due to failure on the primary system, or under fault conditions there may be a very serious drop in voltage.

For giving supply to electrical closing devices where considerable power is demanded, the lead storage battery is almost universal. For charging, a motor-generator set is essential. This battery can be utilised for signalling systems, indicating devices, and if necessary emergency lighting. For the majority of circuit-breakers, 100/110 volts is found to be convenient although for the very large equipments, a considerable saving in the cross section of the copper can be effected by a higher voltage, *e.g.*, 220.

In determining the size of the battery due account must be taken of the drop in conductors up to the coils, as these are rated for the voltage at their terminals.

BIBLIOGRAPHY.

Switchgear Practice, A. Arnold (Chapman and Hall).

Switchgear Handbook, Vol. 2, W. A. Coates and H. Pearce (Pitman and Sons).

" Mechanical Integrity in the Design of Electrical Circuit-Breakers," M. C. Hunter, " Journal I.E.E.," Vol. 87, No. 528, December, 1940, p. 665.

" Force Trips on Circuit-Breakers," W. A. Coates, " Engineering," September, 1939.

" Oil Circuit-Breakers and their Operating Mechanisms," M. C. Hunter, " BTH Activities " October-December, 1946.

" B.S. 116."

" B.S. 936."

CHAPTER XV

CONTROL BOARDS

THE need for some form of power device for the closing of circuit-breakers over 150 MVA is recommended in B.S. 116. The closing of a circuit-breaker on to an existing fault where the short-circuit can exceed the value stated is always problematic if attempted by hand. This has led to the more universal practice of placing the actual point of control at a point remote to the switchgear proper, and much ingenuity has been displayed in both the layout of the remote control board itself and the control room. The location of the control room is often important and in general it should be at a point apart from the generator and switch rooms. This places those in control in relative seclusion, away from noise and distraction, a feature which is particularly important in times of emergency. Whatever the location, it is important that adequate lighting be provided avoiding large and reflection and, particularly, avoiding the use of the swan neck fittings which at one time were common of control boards.

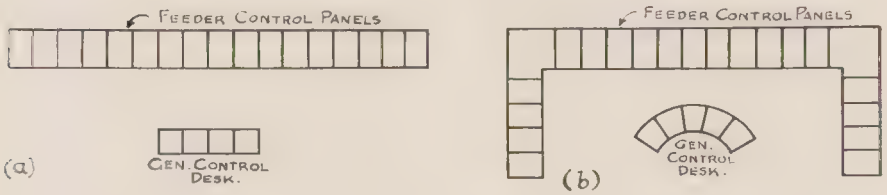


FIG. 15-1.—*Two typical plan arrangements for large Control Boards. Many variations of these are possible to suit conditions.*

The layout of the actual control board will depend largely on the size and extent of the network under control. For generating plants it is generally accepted that the best arrangement is to control all generators at a desk type board placed conveniently to enable the operator to carry out switching operations without walking the length of a long board. All other circuits, *e.g.*, feeders, transformers, will be controlled from an upright board probably behind or facing the generator desks. If the system is extensive, and involves a considerable number of relays these will be accommodated on yet another series of panels. Fig. 15-1 illustrates this general type of layout. For important stations, too, some form of miniature diagram which gives an immediate indication of the state of the network under control will be included. In many cases, a series of panels similar

to those in Fig. 15-2 will be mounted above the control board. Each isolating switch and circuit-breaker will be represented in the diagram by an electrically-operated semaphore, to indicate the open and closed positions. Operation of the semaphore is caused by operation of the device it represents through the medium of auxiliary contacts. An alternative adopted by some is to have lamp semaphores and a more recent development is to form the miniature diagram as part of the main panel when the control switch

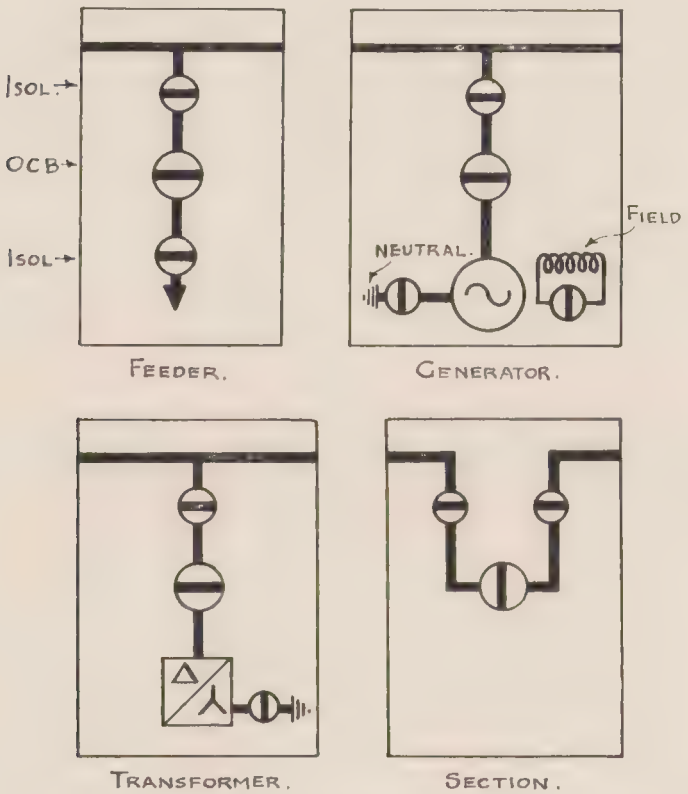


FIG. 15-2.—*Typical Dummy Circuit Diagram Panels, using semaphore indicators. Lamps or lamp indicators can be used with equal facility.*

operating handle forms the indicator. This latter type often includes "light band" instruments which give a shadow indication of the loads, voltages or other quantities of the circuit.

Fig. 15-3 illustrates a typical arrangement of control boards in a power station. Here, the generator circuits are controlled from desk panels placed in front of the upright panels, which accommodates the controls for feeders, rotary convertors and other circuits. A swing panel mounted on a pedestal

close by the desk panels, accommodates the synchronising instruments. This pedestal is also shown in Fig. 15-4.

Another example of this type of layout is given in Fig. 15-5. The form of synchronising adopted in the examples illustrated is one which has become popular recently, namely, with interlocked control switches. Fig. 15-6 gives a diagram for this scheme.

FIG. 15-3.—*Control Board, with generator desks and synchronising pedestal for control of compound filled switchboard, with solenoid operated circuit-breakers (J. & P., Ltd.).*

Where there are not, as is usual, a large number of feeders associated with a few generators, it is convenient to make the control board of all desks or all upright panels. An example of this is a case where a large works has two generators in its own power plant and takes bulk supply in parallel via two power transformers. The supply thus obtained is then fed by two inter-connector feeders to other distributing points in the works. The control desk for this installation is shown in Fig. 15-7 and includes a synchronising scheme similar to that previously described.

Another application of the desk type board is shown in Fig. 15-8. This is for the control of test bed plant operations in the J. & P. Transformer and Switchgear Shops. The desk is erected on a gallery from which the whole test bed area is within view of the controller. Sub-standard measuring instruments for transformer loss testing are housed in a sunken portion of the desk.

The finish of control boards is important. Those illustrated are light grey or sage green, giving a pleasing and restful colour scheme for operators.

FIG. 15-4. — *Synchronising Pedestal for power station control gallery (J. & P., Ltd.).*

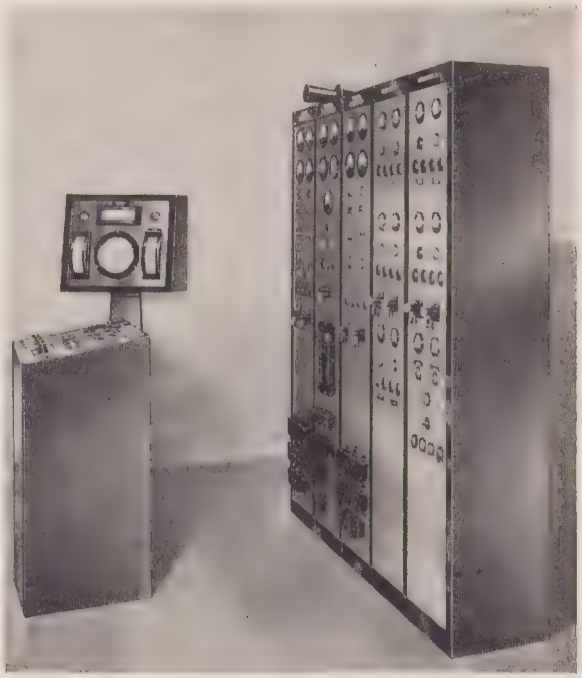


FIG. 15-5.—*Control Board and Synchronising Pedestal (J. & P., Ltd.).*

In the upright type, each circuit is, as far as possible, located on a separate panel, and this is of the cubicle type, totally enclosed, with an access door at the rear. Where required, an illuminating lamp is arranged inside the cubicle to light up automatically on opening by means of a door switch.

The use of miniature indicating instruments has been largely instrumental in the production of neat control boards. Such instruments are also of the flush mounting type and this, together with a minimum of projection on other items, *e.g.*, control switches, indicating lamps, fuses, etc., has enabled clean cut lines to be obtained, and made cleaning easier. The instruments used on the upright boards illustrated are all 3·25 inch diameter dial.

Control switches, built in the form of a miniature controller, are arranged for a number of purposes by a variation of contacts. For circuit-breaker control, they are of the two-way type, arranged to operate in one direction

to close the circuit-breaker, and in the opposite direction to open. A barrel type lock, similar to a car door lock is embodied to prevent inadvertent or unauthorised operation. For safety purposes, provision is made to lock the control switch in the breaker open position. A spring return to neutral

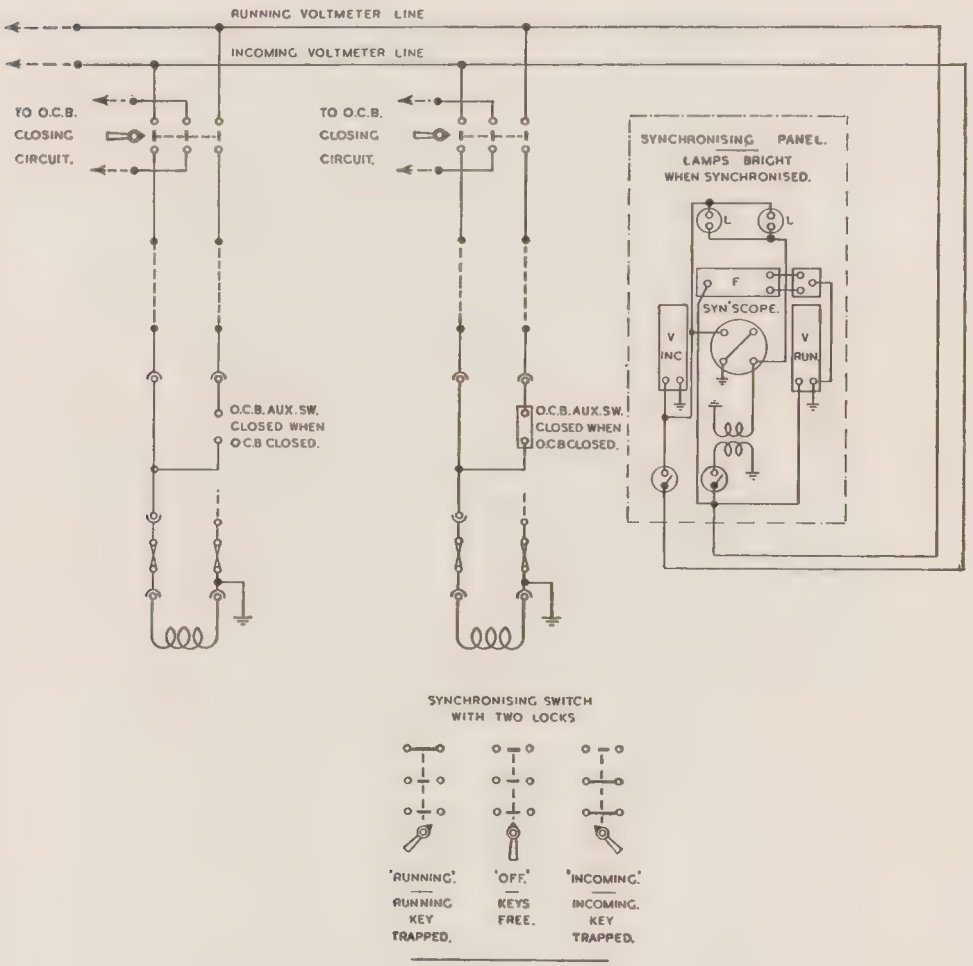


FIG. 15-6.—*Synchronising scheme, using key interlocked control switches.*

is provided. An interlock on the control switch is arranged so that after making a "close" operation, an "open" operation must be made before the next "close" operation. This prevents "pumping" the solenoid closing mechanism with the breaker closed.

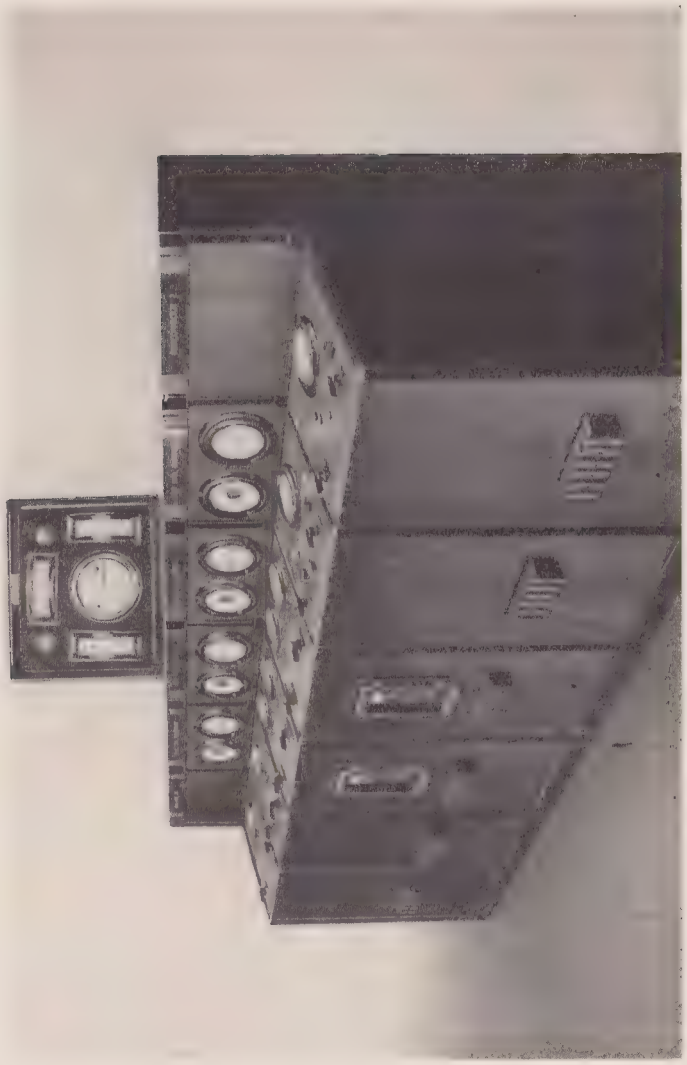


FIG. 15-7.—*Desk pattern Control Board, with synchronising equipment, for metalclad switchboard, with spring closed oil circuit-breakers (J. & P., Ltd.).*

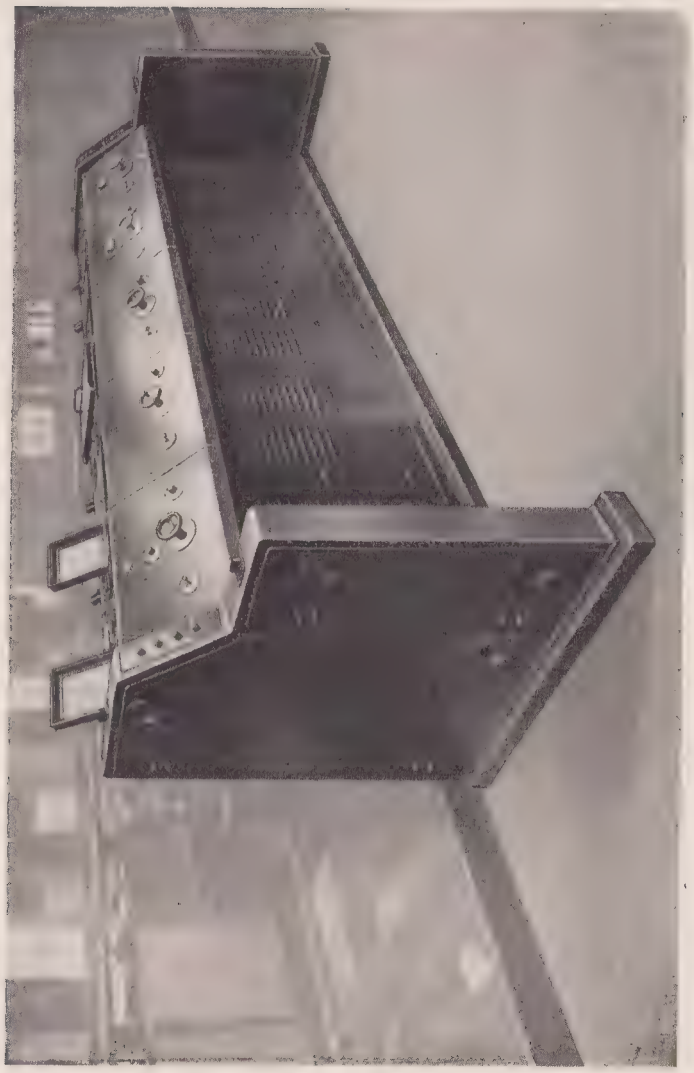


FIG. 15-8.—*Desk pattern Control Board for remote indication and metering of test-bed machines and equipment, installed in large electrical engineering works. (Note the sub-standard meters sunk into the desk for protection).* (*J. & P., Ltd.*)

A standard colour code is necessary for control boards. Generally, this code is :—

Red — Circuit-breaker closed.

Green — Circuit-breaker open.

White — Circuit-breaker opened due to relay operation, *i.e.*, fault tripped.

Amber— To indicate the state of a spring close device, *i.e.*, springs charged or free.

Indication of the white lamp is in addition to that of the green, *i.e.*, on fault tripping, both would indicate.

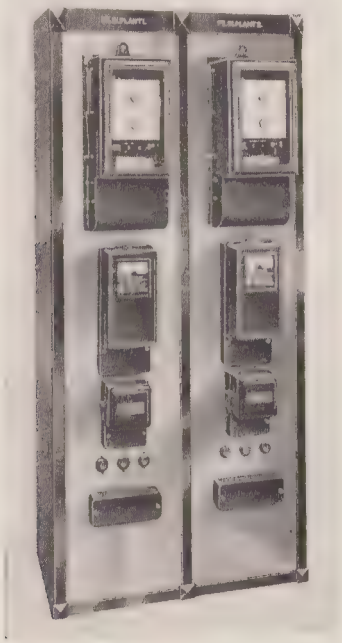


FIG. 15-9.—*Summation Metering Panel (J. & P., Ltd.)*

Internally, the wiring must be arranged in a neat orderly manner, and be in the standard colours, to enable circuits to be traced out simply. Where wiring terminates at a terminal board for leading away to the main switchgear or other apparatus, the terminations should be well clear of the floor ; not less than nine inches is recommended.

Fuses in instrument, control, tripping, and other circuits, must be adequately labelled. In some installations it is sound to colour the fuse holders of certain key circuits in distinctive colours.

Reference has been made to separate relay panels. This can be extended by removing metering equipment from the main control board and using separate meter panels. One example of this is shown in Fig. 15-9.

Although mechanical remote control is sometimes arranged, it must be borne in mind that this hardly meets the recommendation of B.S. 116 because the possible hesitancy of a physically weak operator still remains, with the grave possibility of damage to the circuit-breaker. An example of a control board for remote mechanical control is shown in Fig. 15-10, but the most it can achieve is that it removes the operator from the *immediate*

FIG. 15-10—*Control Board for remote mechanical operation (J. & P., Ltd.).*

vicinity of the circuit-breaker in case of danger. In this type of control, the tripping devices for the circuit-breaker must be at the breaker and *not* on the handle gear at the panel. By this means, the lever and link mechanism between panel and circuit-breaker remains stationary during tripping and, therefore, has no retarding effect.

BIBLIOGRAPHY.

Switchgear Handbook, Vol. II, W. A. Coates and H. Pearce (Pitman and Sons).

Switchgear Practice, A. Arnold (Chapman and Hall).

" REMOTE CONTROL OF POWER NETWORKS," G. A. Burns and T. R. Rayner, " Journal I.E.E.," Vol. 79, 1936, p. 95.

Electric Power Stations, Vol. II, T. H. Carr (Chapman and Hall).

CHAPTER XVI

SUPERVISORY REMOTE CONTROL*

In earlier pages attention has been given to the various types of control boards which are used for the remote control and operation of switchgear. These boards are extremely effective for control over very short distances, but it will be appreciated that when large distribution or transmission systems covering long distances are adapted for centralised control, the difficulties which are encountered preclude the use of this type of equipment. Clearly, the major problems are, firstly, the voltage drop in the long pilot wires which are required, and secondly, the expense of the multi-core pilot cables, which have to be of large cross-section. Further, the control equipment, which is of fairly bulky construction, would not lend itself easily to the compact layout which is essential for this particular application. Even if steps are taken to reduce the dimensions of control switches and lamps, etc., to a minimum where a large number of feeders is involved, the switchgear type control board would still assume sizeable proportions, so that much valuable space would be occupied.

Today, supervisory methods using telephone type equipment are almost exclusively employed for the control of large power networks and distant substations ; the type of control board previously mentioned being used only when it is considered desirable for reasons of safety or convenience to segregate the operator from the switchgear. The development of supervisory control has been coincident with the rapid growth of the electrical undertakings, and the large transmission and distribution networks which are now the general practice. The facilities offered, and the degree of flexibility obtained, together with absolute reliability in operation has resulted in the ever increasing adoption of this form of control.

If a large power network is compared with a telephone communication system, it will be observed that there is a measure of similarity between the operation of selecting a subscriber on the telephone system and ringing his bell, and the selection and operation of a circuit-breaker on the power network. Therefore, if by adopting such apparatus as is employed for the first operation, the requirements of the second are fulfilled, then a ready solution to the problems of remote control is offered. However, at the same time, the highest degree of accuracy in operation must be guaranteed, for whilst wrong numbers or lost calls may only result in undue inconvenience, the wrong operation of a circuit-breaker could have disastrous results. Supervisory control schemes are therefore designed to ensure that mal-operation cannot occur, and circuits are arranged so that if the correct operation fails to be carried out, then nothing at all happens.

For small telephone systems, direct wire communication methods are used, and for larger systems, automatic switching using selectors and relays is adopted. The basic principle of both these methods are employed for remote supervisory control as will be seen later.

* *Contributed by L. H. Berridge and J. T. Ludlam of J. & P. Switchgear Department.*

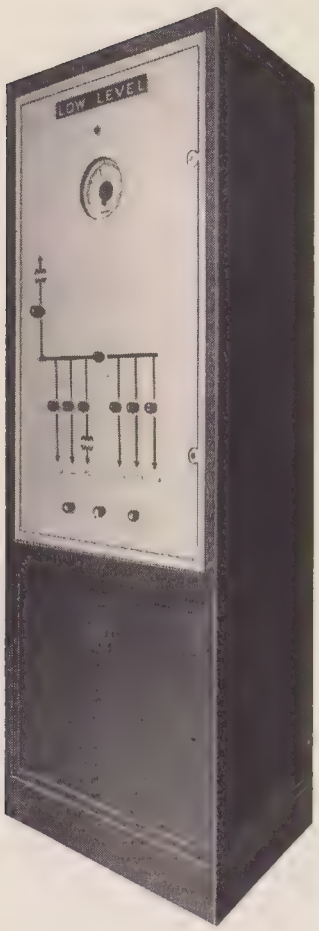


FIG. 16-1.—*Supervisory Control Board for a Single Substation (Standard Telephones and Cables Ltd.).*

Although supervisory control is closely associated with power engineering, it should be appreciated that it is essentially a branch of telecommunication engineering and so to be fully conversant with the subject, it is necessary to have a clear understanding of both aspects of electrical engineering. In fact, supervisory control constitutes an important link and contact between power and telecommunication engineering.

Simple Direct Wire Control.

The simplest form of supervisory control suitable for switchgear and associated equipment, is the direct wire method, which is economic for a distance up to approximately one mile from the control point. Such schemes make use of multicore pilot cables between the apparatus which is to be controlled and the supervisory control equipment and by their simplicity and avoidance of coded signalling methods are particularly attractive. The type of cable employed depends mainly upon local conditions and proximity to other electrical circuits, but in general, it is a paper insulated, lead covered type, with steel tape or wire armouring where such additional protection is warranted, and small gauge conductors in keeping with the low voltages and currents required by the apparatus used.

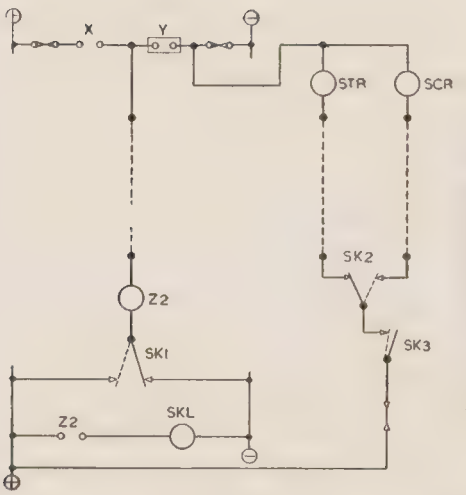
Such schemes usually operate from a d.c. supply derived from a battery at the control station. In some instances, however, the supply may be taken from the remote substation, where the battery is made common to the switchgear and control equipment.

A typical installation of the direct wire method serving a main line railway substation is illustrated in Fig. 16-1 and Fig. 5-2 (p. 63). The former shows the supervisory control panel, and the latter the switchgear which it controls. As will have been noted from the context, the switchgear is of solenoid-operated, metalclad type. Interposing relays are employed for the operation of the circuit-breaker closing and tripping circuits, and these are mounted inside the instrument panels on the switchgear. The necessary auxiliary switches are associated with the operating mechanisms of the circuit-breakers and load-breaking switches.

Combined semaphore type control key indicators are mounted on the front of the control panel suitably disposed on a distinctively coloured single line diagram of the switchboard at the remote substation. Alarm relays, alarm bell, fuses, etc. are fitted inside the panel and a hinged door is provided at the back for access. In this particular installation the d.c. supply was taken from the remote substation.

The accompanying diagrams are illustrative of the control and indication circuits which were employed in this simple project. Schematic diagram Fig. 16-2 shows the control and indication circuit for one of the circuit-breakers, which, as will be noted from the position of the auxiliary switches, is in the " Open " position. Thus, if the control key is turned to the " Close " position, contacts SK2 and SK3 will take up the alternative positions shown, causing a current to pass through the " Close " interposing relay SCR. The contacts of this relay will close, completing the contactor coil circuit, thereby closing the breaker as will be seen by reference to schematic drawing C of Fig. 16-3.

It will be noted from Fig. 16-2 that contact SK1, which has moved in unison with contact SK2, will have taken up the alternative position shown and remained there. At the same time, the circuit-breaker auxiliary switch Y has opened and X has closed, therefore no current will pass through the alarm relay Z2. However, should a fault now occur on one of the power



SYMBOLS

W	Circuit-Breaker Auxiliary Switch—Closed when O.C.B. closed.
X	Circuit-Breaker Auxiliary Switch—Closed when O.C.B. closed.
Y	Circuit-Breaker Auxiliary Switch—Closed when O.C.B. open.
SCR	Interposing Relay for Closing.
STR	Interposing Relay for Tripping.
SK1, SK2 and SK3	Semaphore Key Contacts.
SKL	Semaphore Lamp.
Z2	Alarm Relay.
AC	Alarm Cancellation Switch.
AB	Alarm Bell.
COS	Change-over Switch (from Local to Supervisory Control).
C	Contactor.
B	Circuit-Breaker Closing Coil.
OL and RSG	Protective Relays.
T	Circuit-Breaker Trip Coil.

FIG. 16-2.—*Schematic Diagram for Simple Direct Wire Scheme, showing Supervisory Control and Indication Circuits.*

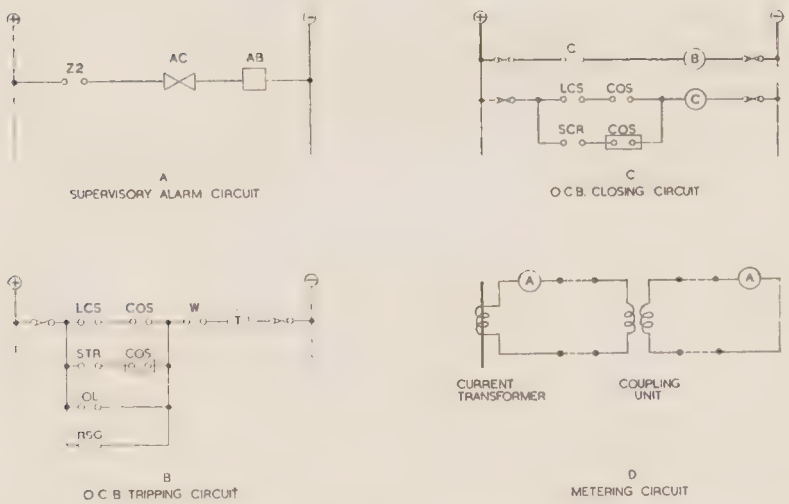


FIG. 16-3.—*Schematic Diagrams for Simple Direct Wire Scheme, showing Supervisory Alarm and Metering Circuits together with Circuit-Breaker Closing and Tripping Circuits (For symbols see Fig. 16-2).*

feeders causing the circuit-breaker to open, auxiliary switch X will open, and Y will close, but this time a current will flow through the relay Z_2. This relay illuminates (or more distinctively " flashes ") the semaphore lamp SKL and also rings the audible alarm (see diagram A, Fig. 16-3). The signal may be accepted by turning the key through 90° to the " Open " position, which returns contact SK_1 from the dotted position cutting off the current to the alarm relay. The lamp in the semaphore key is therefore normally extinguished.

The control panel is provided with a station name facia which is illuminated when one of the alarm relays operates, an advantage when several control panels are installed, since the attention of the operator is drawn immediately to the panel which is signalling.

Other direct wire control methods employ coloured lamp signals with separate control keys, details of which are given later.

FIG. 16-4.—*Coupling Unit for Direct Wire Metering* (*For Connections in Current Transformer Circuit, see Fig.* 16-3.) (*Standard Telephones and Cables Ltd.*).

SIMPLE DIRECT WIRE METERING.

With direct wire schemes, where a high degree of accuracy is not essential, provision may be easily made for simple metering facilities. Direct wire metering enables continuous reading of current or voltage to be made over the multicore pilot cables between the switchgear and control panel.

A coupling transformer is used in conjunction with the voltage or current transformer on the switchgear. The primary winding of this transformer or coupling unit is connected to the secondary of the instrument transformer, either in parallel for voltage readings, or in series for current readings. The secondary side of the coupling unit is connected to the pilot cable, at the remote end of which are provided the necessary instruments. A typical

coupling unit is shown in Fig. 16-4, and Fig. 16-3 illustrates the method of connection in a current transformer circuit. This method of remote metering was used in the control scheme described earlier.

PILOT LINE NETWORKS.

In cases where control has to be exercised over relatively long distances, direct wire schemes are prohibitive due to the high cost of providing and laying the necessary multicore cables. One answer to the problem is to restrict the number of cores to an absolute minimum, and carry out all signalling over these few wires by means of a system of coded impulses. Another solution is to use separate frequency channels superimposed on the existing power lines, and details of such a method are given later.

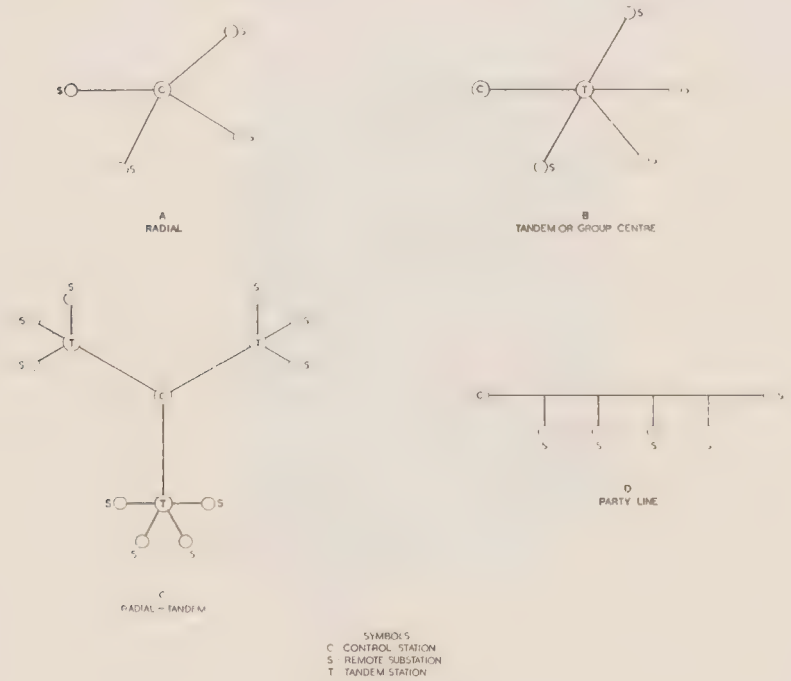


FIG. 16-5.—*Typical Pilot Line Arrangements.*

On supply systems, where coded impulse methods are employed, much saving in cost is to be obtained by interconnecting the substations in order to use the pilot wires as economically as possible. The actual choice of such a pilot line network is dependent upon local conditions, the layout of the substations, and the extent of the supervisory control. Consideration must also be given to the geographical layout, and in the case of existing undertakings, to any pilot wires which may already be available.

Typical methods of linking remote substations to the control station are shown in Fig. 16-5. Diagram A illustrates the radial system in which the control station is situated centrally, with separate pilot lines radiating to the

outlying substations. This should be compared with diagram B which shows the tandem or group centre system. Here the control station is connected to a tandem station from which further lines radiate. The radial-tandem system which is shown in diagram C, is a combination of A and B. This method is economical in conductors between the tandem and control stations, particularly in large schemes involving very many substations, but may result in slight delay of the signals to the central point if more than one substation in any one group wishes to signal at the same time.

Yet another arrangement is shown in diagram E. This is known as the omnibus or party line method. In practice, a party line would serve a number of related substations on a common line, as for instance substations on an electrified railway system or a long " spur " line serving numerous substations.

The pilot lines referred to above comprise one or more pairs depending on the overall scheme and a variety of circumstances. Where conditions warrant it, one pair only of conductors between adjacent stations can provide all services comprising control, back indication, telephony and telemetering. On the other hand, additional conductors, if available, enable schemes to be simplified and the final choice in any selected case can only be made when all the salient factors have been carefully assessed.

For relatively long distances where lines connecting distant load centres are rented from the postal administration, it is especially necessary to cater for all the services over the minimum number of wires, and for such needs, specially designed schemes have been evolved. In less well developed areas where longer distances separate the various load centres but economic or technical considerations still warrant the use of such control and telemetering schemes, resort can be made to equipment employing telegraph carrier superimposed on the H.T. power lines serving the electric network. Here, the main consideration is cost of the terminal equipment particularly at the higher voltages, since this must be specially designed to meet the very exacting requirements of the carrier current circuits, and also to suit the insulation level of the power line. Therefore this method may only be justified in relatively few cases.

Coded Signalling Systems.

The semi-pictorial schematic drawing, Fig. 16-6, shows a typical scheme for the control and indication of a remote switching station from a central station. It will be appreciated that in actual practice, more than one substation could be controlled from the panel, but for the sake of simplicity, only one switching station has been considered and illustrated by a single metalclad panel.

Equipment suitable for the generation and transmission of coded signals is provided at both the control and switching stations. This equipment is arranged to operate in a similar way to that of the automatic dialling telephone, in that various signals may be transmitted and received in the form of a series of impulses of current representing different numbers. These signals are sent from the control room when one of the controls is initiated, whilst those sent from the switching station originate on the operation of a circuit-breaker mechanism, or the alarm equipment, etc., to mention but a few instances.

To close a circuit-breaker the operator moves one of the keys, which actuates the code sender. The latter selects the line and transmits a signal via the pilot wires which is picked up by the code receiver at the remote

substation. The code receiver there sorts out and checks the signal which is passed on to the control equipment where the necessary operation is carried out.

If a circuit-breaker opens automatically, signals are transmitted from the remote substation and sent to the control station in a similar way, so that alarm and indication is given.

As mentioned earlier, special precautions must be taken to ensure correct operation. One method which is employed to achieve this makes use of specially compiled codes. Each code may consist of three numbers or digits A, B, and C, but all codes have one thing in common, that A plus B plus C is a constant value. On receipt of any code at the distant end, it is checked for the correct number of digits and also for the correct total, and only when these conditions are satisfied can operation proceed.

A second method which is used is the " preselection check back system." In this case, a preselection code is transmitted to the switching station before the control operation can be carried out. This code picks out the unit which is to be operated, and when this has been successfully achieved a check back code is sent to the control station. If the check back code agrees with the code originally sent, then a special signal is given to the operator who can proceed with the final operation. This causes a further signal to be sent down the line, which is followed by the appropriate position change indication back to the control station, thus confirming that the operation has been carried out correctly. The line is then cleared for the next operation.

Another method which is perhaps more frequently used in practice employs uniselectors, or equivalent mechanisms at both the control and switching stations, these being arranged to rotate in sympathy with one another and employing a checking system to ensure that the selectors rotate in step and are at all times correctly synchronised.

Voice Frequency Signalling Systems.

Whilst direct current is generally used in supervisory control schemes, the use of voice frequency currents permits of control over much greater distances. In fact, in the case of very long lines, and where amplifiers must be used to reduce the overall attenuation, d.c. signalling cannot be employed.

The method of signalling by V.F. is very flexible for supervisory control purposes. Whilst multi-frequency working is generally used, and has many advantages including maximum speed of operation, the employment of a single frequency is also possible, and is in fact used in certain cases. In the case of multi-frequency working, discrimination between incoming and outgoing signals is effected by utilising two different frequencies, which thus correspond to the two directions of current employed in d.c. signalling. With single frequency working, discrimination is accomplished by means of " short " and " long " impulses, and is, therefore, somewhat slower in operation.

A check back system employed by one manufacturer requires four signalling channels, two from the control station to substation for "selection" and " operate " signals, and two from substation to control station for " open " and " closed " back-indication signals. The two latter channels are also used for check back signalling and metering. Further channels can be provided for special functions such as inter-tripping signals or a continuous metering channel, and the two-wire channel can also be used for telephony when not in use for supervisory control.

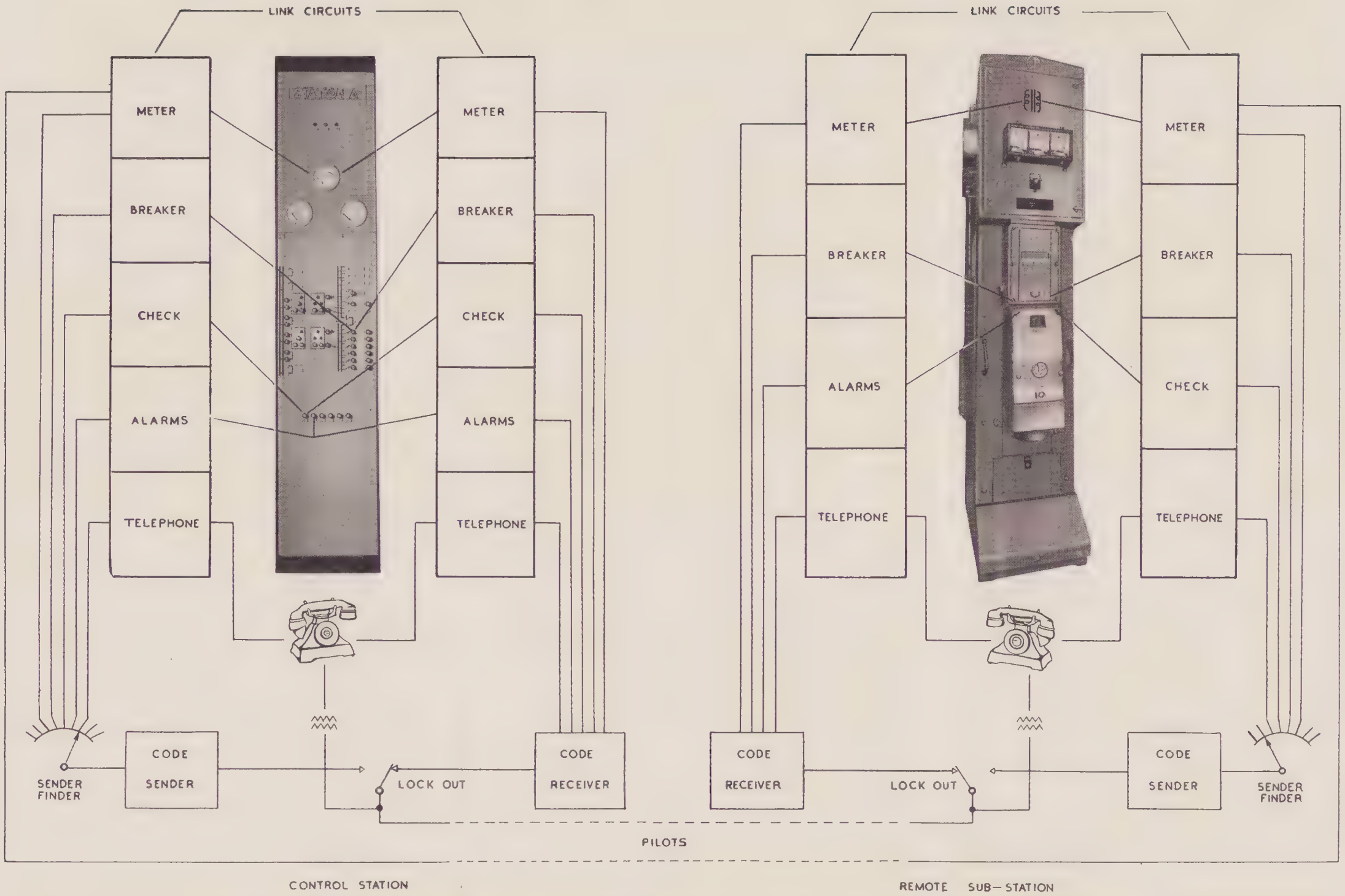


FIG. 16-6.—*Semi-pictorial Schematic of Typical Supervisory System (Standard Telephones and Cables, Ltd. and Johnson & Phillips Ltd.).*

Each channel is provided by the use of a separate frequency, and the signalling current is generated by a thermionic valve oscillator tuned to the channel frequency. This current is transmitted to the line as a continuous signal during the periods that d.c. would be applied on a d.c. signalling system, and impulsing is transmitted as interruptions of the voice frequency signal. At the receiving end, the channel frequency is separated from the other channels by means of a tuned filter, and passes to an amplifier-receiver which translates voice frequency signals into d.c. signals to operate the receiving relay circuits. The frequencies employed lie between 300 and 3,000 cycles per second. Since voice frequency receivers are sensitive to frequencies in the speech band, special guard circuits are necessary to prevent the operation of the receiving circuits during a telephone conversation over the same pilots. One feature of these guard circuits is that the initial voice frequency signal must persist uninterrupted for a definite minimum time before it becomes effective.

An example of a voice frequency signalling system is shown in Fig. 16-7. This diagram indicates the general circuit arrangements of the line and terminal apparatus connecting the central indicating station, and an outlying station over a line in which an amplifier is fitted. In this case, three different frequencies are employed, namely, 288, 576 and 1440 cycles per second, these being supplied from a small multi-frequency motor-generator.

The three receivers at the ends of the line are of the amplifier-rectifier type, a sensitive relay being connected in the plate circuit in each case. One receiver is provided for each of the three frequencies, which are confined to their respective receivers by means of the filters.

The actual transmission of the signals is effected, at the central indicating station, by means of relays X, OP and PP, and at the outlying station by relays LF, MF and HF. The filaments of the 288 cycles receivers are continually energised, so that the application of this frequency at either end of the line by the operation of relay X or relay LF, closes the filament-circuits of the 576 and 1,440 cycles receivers in readiness to receive the subsequent trains of signalling impulses. The latter control the operation of relays B1 and B2 or L and AA, which in turn operate the d.c. indication or control circuits.

Carrier Current Channels on E.H.T. Power Lines.

When an electricity supply network covers an area in which stations are separated by considerable distances, the cost of installing pilot wires may render remote supervisory control uneconomical. In such cases it is sometimes the custom to rent lines from the telephone administration, but this has the inherent drawback that the continuity and maintenance of the lines is not under the control of the electricity supply authority, and since such rented lines are usually incorporated in multi-core cables along with ordinary telephone circuits, there is always the possibility of interruptions being caused by the telephone administration personnel.

A reliable alternative is to employ carrier currents, superimposed on the power lines. Much progress has been made in this direction in recent years, and carrier channels have been installed to operate on power lines up to the highest voltages. A full range of facilities can be provided whether pilots or carrier channels are employed, and justification for the use of carrier channels is to be sought mainly in a comparison between respective costs.

It should, however, be emphasised that carrier currents superimposed on the power lines provide an inherently reliable channel since, firstly,

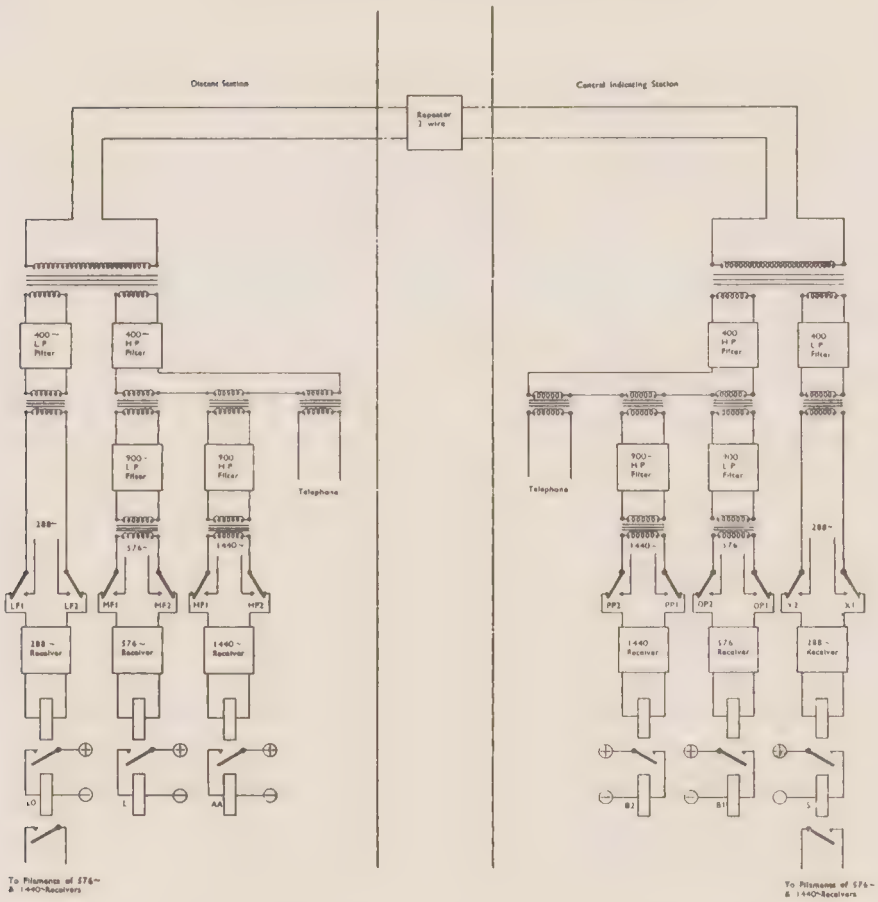


FIG. 16-7.—*Schematic Diagram of Voice Frequency Signalling System (The Automatic Telephone and Electric Co., Ltd.).*

power lines have a very high factor of safety, and secondly, even if breakages of the power line occur, carrier communication may still be possible.

The carrier current principle is briefly explained by reference to Fig. 16-8. At station A an oscillator O generates a carrier frequency usually in the range of 80 to 170 kilo-cycles per second, which is modulated at M with the signals or speech to be transmitted. The filter portion of the protective and filter unit PF together with the line coupling condensers K and the tuned choke coils L, form a band-pass filter which allows the carrier frequency and its associated side-bands to pass to the power line, while the choke coils L prevent them from being dissipated in the terminal power apparatus. The condensers K, having a low capacity, prevent power frequency currents flowing into the carrier apparatus, and are insulated for the full line voltage, while the unit PF incorporates additional protection in the very unlikely event of the failure or flash-over of a condenser. At the station B, the line coupling apparatus passes the carrier frequencies to the demodulator D1, where they are rectified to reproduce the original signals.

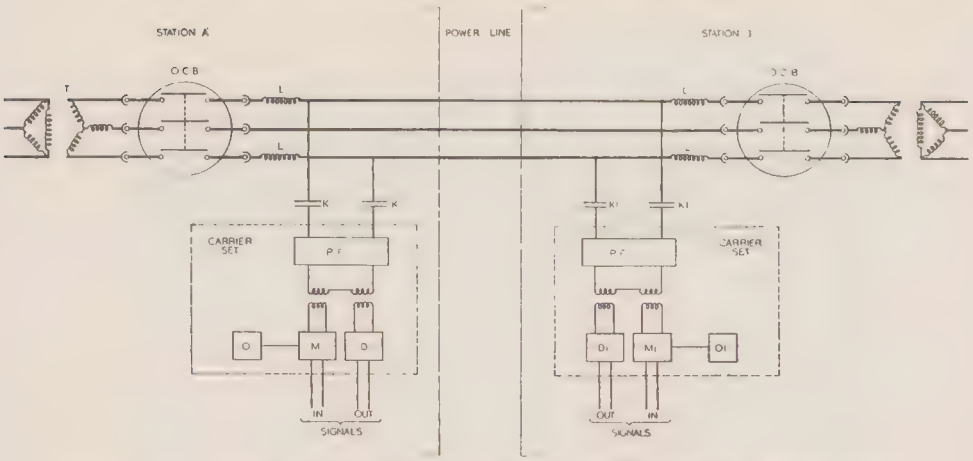


FIG. 16-8.—*Schematic Diagram of Carrier Current System (The General Electric Co., Ltd.).*

Signalling in the reverse direction is effected in a similar manner, via oscillator O1, modulator M1 and demodulator D1, and since a different frequency is used for each direction, signalling in both directions is possible simultaneously.

Bridging arrangements enable the carrier channel to be maintained across switching points at times when the power line is open-circuited, whilst portable choke coils may be employed to earth the line when maintenance work is being carried out.

METERING.

The method of simple direct wire metering which has already been described has obvious limitations, and where the number of pilots available is restricted, other methods may be preferred. In such instances, special instruments are provided at the remote substation, and these originate signals which are transmitted along the pilot wires or carrier channels to operate the supervisory instruments at the distant end. Whilst the means of originating signals for different types of meter readings vary, the schemes of metering described in the following can be arranged to cover most requirements.

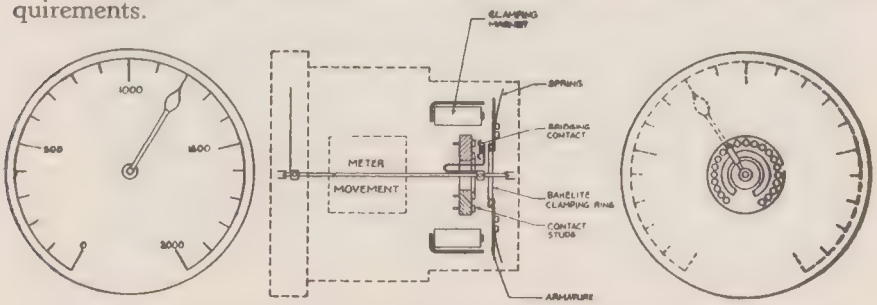


FIG. 16-9.—*Schematic of Contact Metering Transmitter (The Automatic Telephone and Electric Co., Ltd.).*

Where continuous meter readings are not required, contact metering can be effectively employed. This system utilises a transmitting instrument

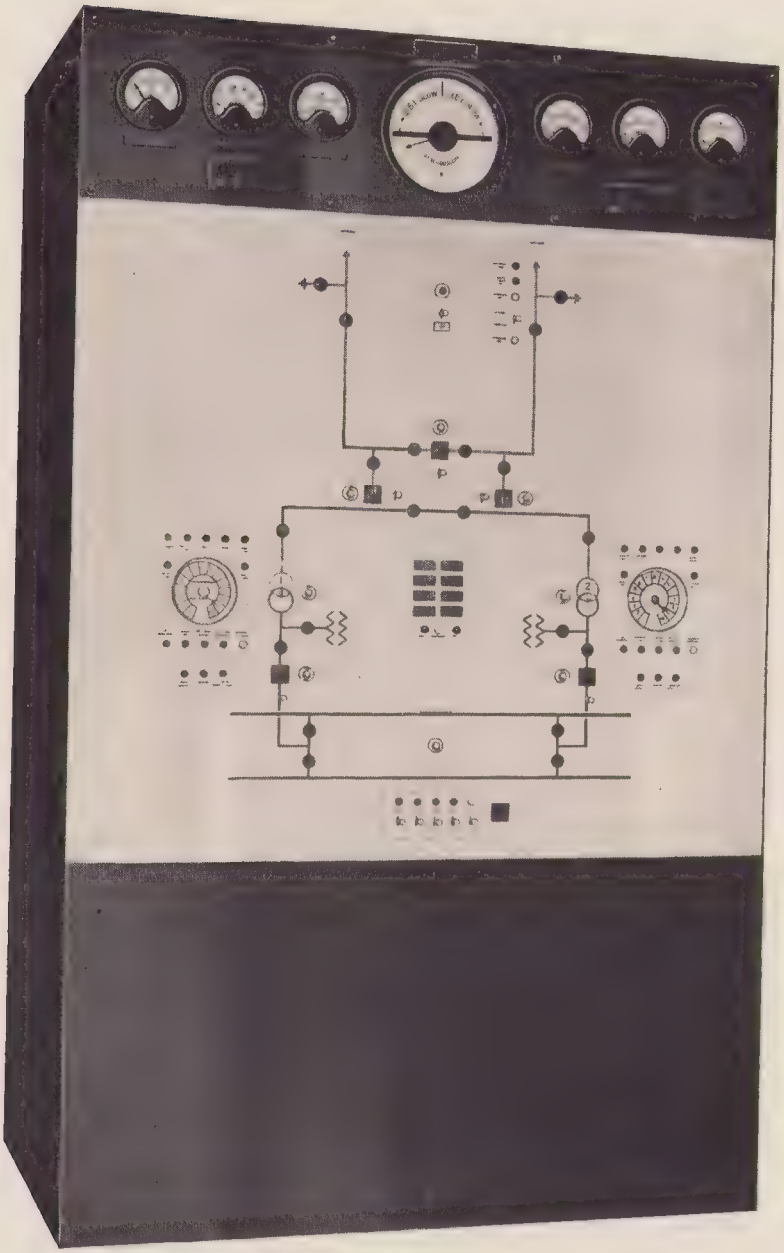


FIG. 16-10.—*Supervisory Control Board showing Tap Position Indicators complete with Alarm Signals, etc. situated on either side of the line diagram (The Automatic Telephone and Electric Co., Ltd.).*

at the remote substation, and a follower instrument at the control station. The transmitting instrument, illustrated in Fig. 16-9, has, in addition to the usual movement, a light contact fitted to the spindle which is disposed to work over, but without touching, a series of radial contacts. After the meter has been selected, depression of the "Operate" key causes two sectors, actuated by small electro-magnets, to press the spring contact on to one of the radial contacts. The supervisory control apparatus at the substation responds to the circuit thus established and sends impulses over the pilots, the number or coded signal being dependent upon the position of the pointer. The receiving instruments may be either ordinary or "both-way" uniselectors fitted with suitable scales. Old readings can be cancelled and new readings can be set up on each group of meters at the rate of about 10 to 12 meters per minute.

Contact metering is suitable for any kind of pilot line, since the impulses can be either d.c. or voice frequency. This system has been designed for readings of amps., volts, VAr and power factor. It will be appreciated that the readings are "spot" readings, *i.e.*, they remain displayed on the mechanical meters until new readings are taken.

Contact metering methods are also employed to give remote indication of the positions of automatic tap changers fitted to power transformers. Fig. 16-10 shows a typical control panel fitted with two tap position indicators.

Where continuous meter readings are required together with a higher degree of accuracy, voice frequency methods are employed. In one such system, the principle is to transmit a series of current impulses of voice frequency, such that a particular number of impulses corresponds to a predetermined scale deflection of a remote instrument.

Fig. 16-11 shows the essential components of the transmitter. A semi-circular vane A is fitted to the rear end of the spindle movement. Behind this vane is a toothed disc which is situated in front of a semi-circular mirror B. When the instrument reads zero, all the teeth of the disc are covered. The teeth are scanned by a device comprising two lens prisms mounted on a rotating frame driven by a synchronous motor. A gas filled lamp D is provided, and the apparatus is so arranged that the light from this lamp is caused by the prisms to fall on the periphery of the disc, where it is reflected by the mirror on to a photo-electric cell through the gaps in the teeth. The light falling on to the photo cell is therefore interrupted by the vane, and also by the teeth on the disc. Thus, if the output of the cell is amplified, impulses of current may be transmitted to the receiving instrument. The latter comprises a milliammeter coupled to a suitable receiving and rectifying circuit.

This system can be operated above the audio range, and by means of suitable filters, can be rendered absolutely continuous without in any way impeding the sending of the full range of supervisory control signals or telephonic communication.

Another method which is used is known as the Variable Frequency Continuous Metering System. One form of this employs a transmitting instrument which is basically a meter of standard design, but which incorporates a small variable condenser connected in the tuning circuit of a VF oscillator in such a way that the frequency output is a function of the meter reading. This variable voice frequency is amplified at the receiving end of the line, cleaned of harmonics, limited in peak voltage and passed through a discriminating network, the output of which in d.c. current is

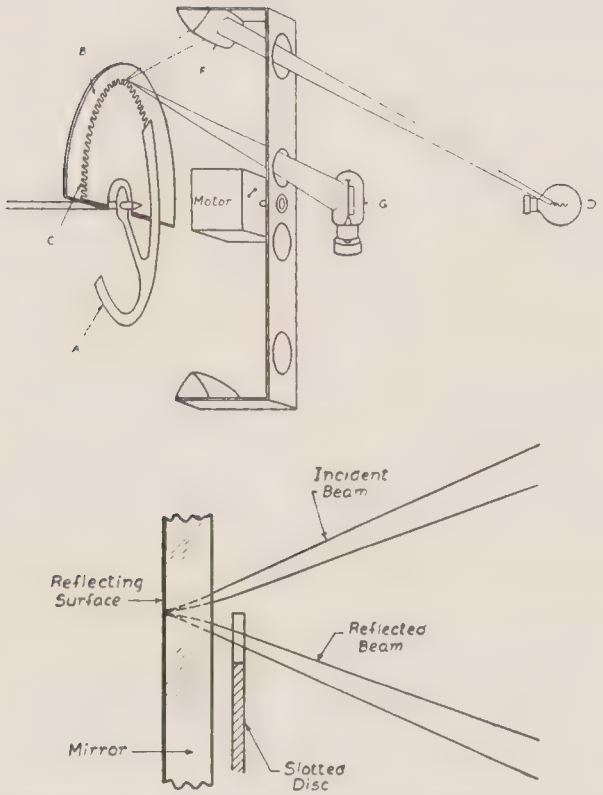


FIG. 16-11.—*Schematic of Photo-telemetering Transmitter (The Automatic Telephone and Electric Co., Ltd.).*

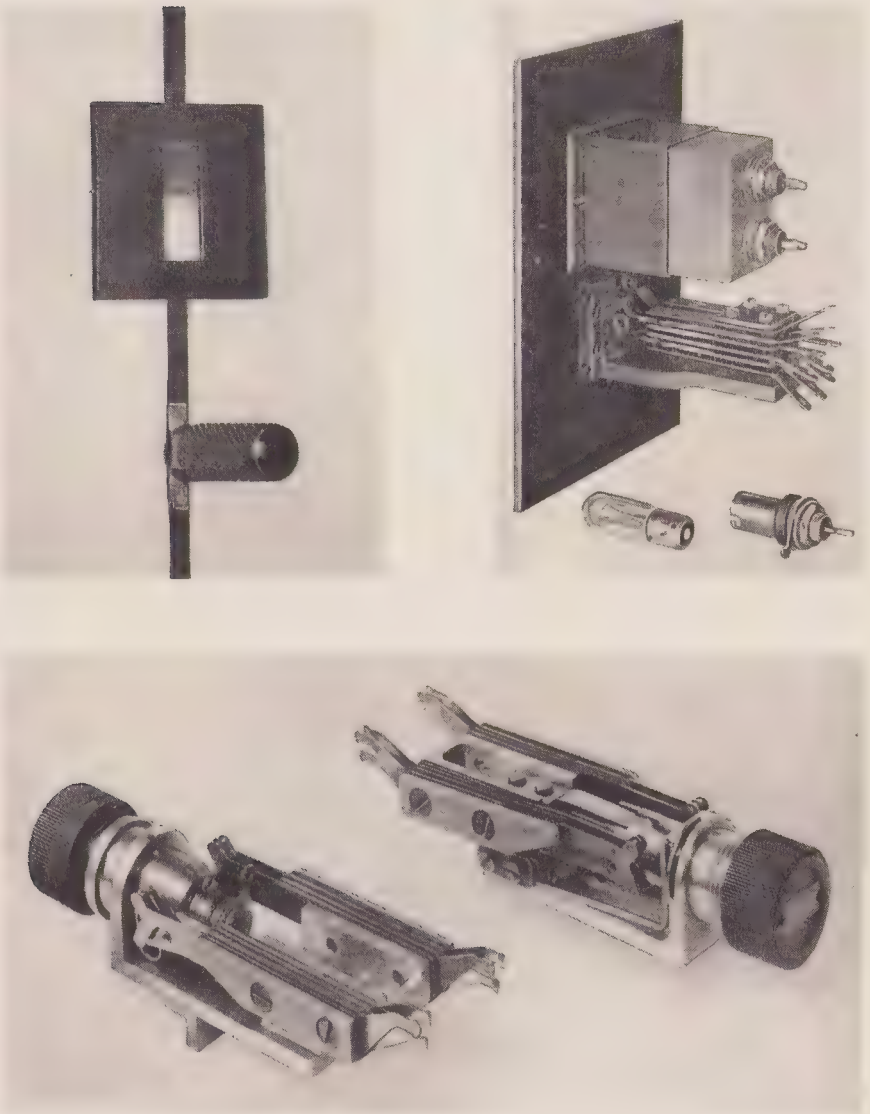


FIG. 16-12.—*Typical Supervisory Control Units (Upper: The Automatic Telephone and Electric Co., Ltd. Lower: Standard Telephones and Cables, Ltd.).*

inversely proportional to the frequency of the input. A d.c. indicating meter is connected to this output circuit and is calibrated to correspond with the distant transmitting meter.

The frequency band corresponding to one meter circuit is only 50 cycles, so that by the use of filters several such circuits can be accommodated simultaneously on a channel otherwise suitable for normal speech transmission.

CONTROL KEYS AND INDICATORS.

Two types of control unit used in conjunction with supervisory schemes are given in Fig. 16-12. The type shown in the upper illustration includes an illuminated indicator, which comprises a square aperture divided into two halves, each of which is fitted with coloured frosted glass.

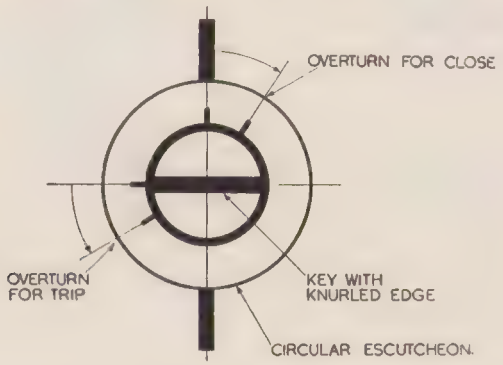


FIG. 16-13.—*Line Drawing of Semaphore Key.*

The glasses are coloured red and green to indicate breaker "Closed" or "Open." Miniature lamps are fitted in a box type holder behind these glasses, and these provide the necessary illumination. The control key below the semaphore indicator is of the Post Office pattern, and the contacts may be arranged both in number and mode of operation to suit the control circuits. If required, the control key and semaphore indicator may be used independently.

The lower illustration C shows a combined control key and semaphore indicator to which reference has been made earlier. The plastic knob of the control key has a white translucent centre. Behind this is fitted a miniature lamp for signalling purposes. A coloured line can be provided on the white centre to represent a circuit-breaker symbol as shown in the illustrations. Rotation of the knob operates the contacts fitted at the back, these contacts being arranged to suit circuit requirements. Fig. 16-13 is a line drawing to illustrate the operation of the semaphore key. The coloured line on the front is at right angles to the line of the diagram and therefore indicates that the circuit-breaker is in the "Open" position. If the key is rotated through 90°, and then overturned to the position marked, the closing of the contacts will cause the operation of the remote circuit-breaker. When the key is released, it will return under the action of a spring to the vertical position, but will leave one or more of the contacts closed. These contacts are arranged in such a manner that should the circuit-breaker open automatically, the lamp inside the knob will be illuminated, and an

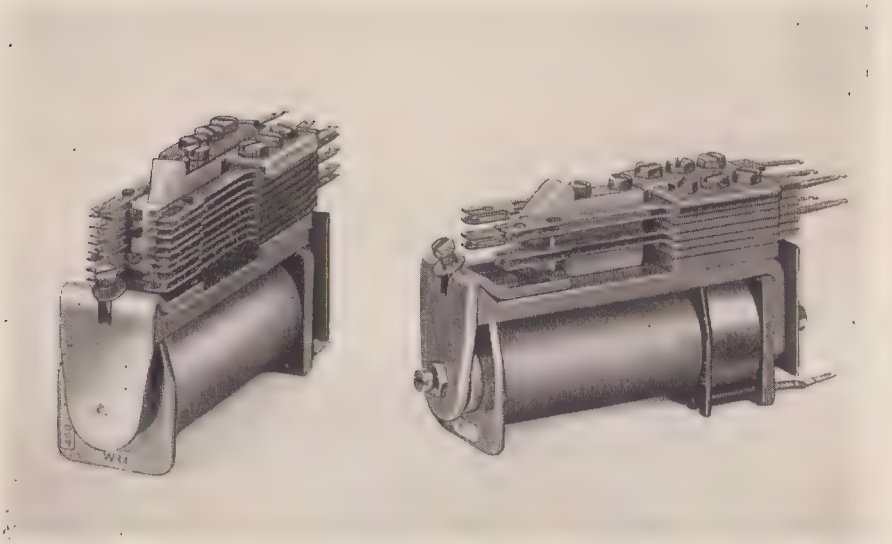


FIG. 16-14.—*Typical Relays for Supervisory Control—Left, Fast Acting Relay; Right, Slow Acting Relay (Standard Telephones and Cables, Ltd.).*

audible alarm will be given. To cancel this, the knob is rotated through 90° until the coloured line is in the horizontal position, when the audible alarm will be cancelled leaving the lamp alight. The reverse procedure is adopted when it is necessary to open a circuit-breaker.

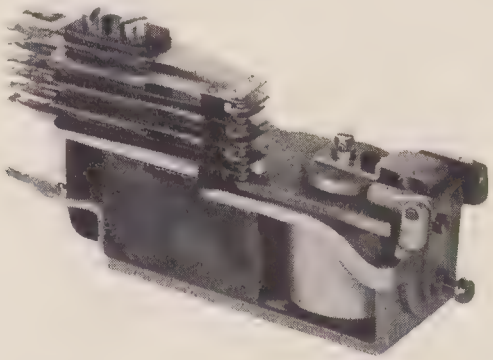


FIG. 16-15.—*Magnetic Locking Relay (The Automatic Telephone and Electric Co., Ltd.).*

Slip-over caps may be provided for these semaphore keys to indicate a breaker which is out of commission, or isolated for maintenance. Push operation can be provided on keys of this type if required, which can thus be used for a variety of purposes, including check signalling, telephones, etc. These keys are designed for one hole fixing and lend themselves readily for use on compact line diagrams, particularly where future extensions are envisaged.

The control panel shown in Fig. 16-24 incorporates a separate control key with three miniature lamps coloured green, white and red. The colours green and red are used to indicate that the circuit-breaker is closed or open, and the white lamp is used for a check signal.

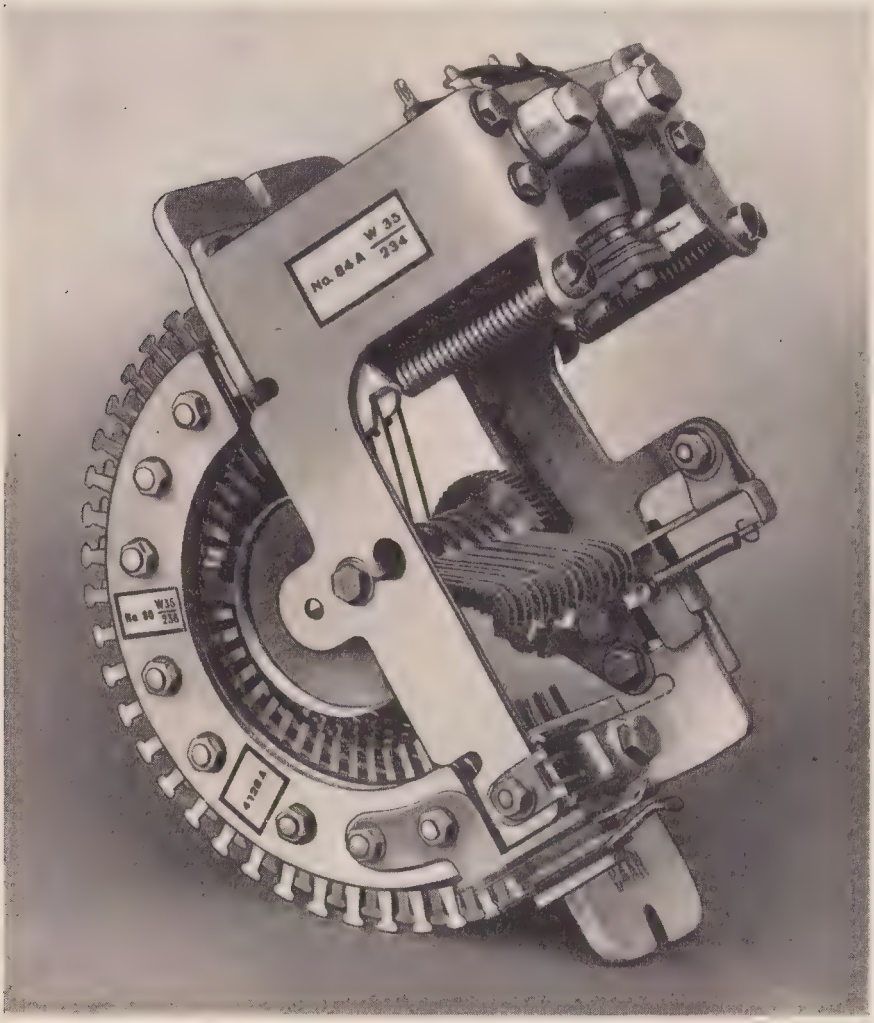


Fig. 16-16.—*The Uniselector (Standard Telephones and Cables, Ltd.).*

Relays.

Relays used in supervisory control follow standard telephone practice, and the majority of the patterns have been proved in such service over a number of years in all parts of the World, operating unfailingly under the widest extremes of temperature and climate. The basic design is that standardised for future use by the British Post Office and manufactured in hundreds of thousands yearly. These relays are of various types depending on the specific duty demands.

Probably the most common of all the relays is the fast-acting type, which can be arranged to give almost any combination or sequence of contacts, to suit given circuit conditions. This relay can be quite easily utilised as an interposing relay providing the currents are small. The construction of the relay is shown in Fig. 16-14 (left), and it will be seen that it consists essentially of a central core of high grade magnetic iron, suitably wound to form the operating coil, and a pivoted armature carrying an insulated arm which actuates a bank of contacts when the relay is energised.

A second type is the slow-acting pattern, which is generally similar in construction to the fast-acting relay, with the exception that a solid copper ring is fitted round the core either at the " heel " as shown in Fig. 16-14 (right), or at the armature end. In the latter case, when the relay coil is energised, the growth of flux generates eddy currents in the ring or " slug," as it is called, thus delaying the rate of rise of flux. Similarly, when the relay coil is de-energised, the rate at which the flux dies away is also delayed, the effect being that the relay is slow operating and releasing. When the slug is fitted at the heel end, the relay is fast operating and slow releasing.

Polarised relays are frequently used, and these may be divided into two general types, the magnetic locking relay, and the polarised line relay which is extremely sensitive. The magnetic locking relay shown in Fig. 16-15 is so designed that when a current is passed through it in one direction, it locks, and can only be restored to its original position if the current is passed through it in the reverse direction. If the relay contacts are used in conjunction with a lamp circuit, then clear indication may be given to show whether a normal or a reverse pulse has been received over the line. These relays are frequently used in the various indicating schemes.

The Uniselector.

A typical uniselector as used in supervisory control schemes is shown in Fig. 16-16. It will be noted that essential parts comprise, a driving magnet, armature, pawl and ratchet wheel, wiper assembly, together with the contact bank and mounting frame. The operating magnet, and its associated pivoted armature, is fitted at one end of the switch framework, whilst the operating pawl attached to an extension of the armature engages with the ratchet wheel. The latter is mounted on the central shaft carrying the wiper assembly. Contact with the wipers is made by means of brushes which form a part of the contact assembly. A set of interrupter contacts is provided so that the uniselector may be given a stepping or a self-drive action. The latter is employed for returning the wipers to the home position when an operation has been completed.

When the operating coil of the uniselector is energised, the armature is attracted against the action of a restoring spring, and the pawl rides over a tooth of the ratchet wheel. During this operation the ratchet wheel and wipers are prevented from moving backwards by a cantilever spring. When the operating coil is de-energised, the armature is restored to its original position by the restoring spring, thus rotating the ratchet wheel and wiper one step.

A simple uniselector circuit is shown in Fig. 16-17, which is for a three level uniselector. Each of these levels, which consist of twenty-five contacts, has been shown separately with its associated wiper. These wipers are coupled together and cannot move independently. By energising and de-energising the operating coil of the driving magnet, the wipers are caused to step round the contacts of their respective levels simultaneously.

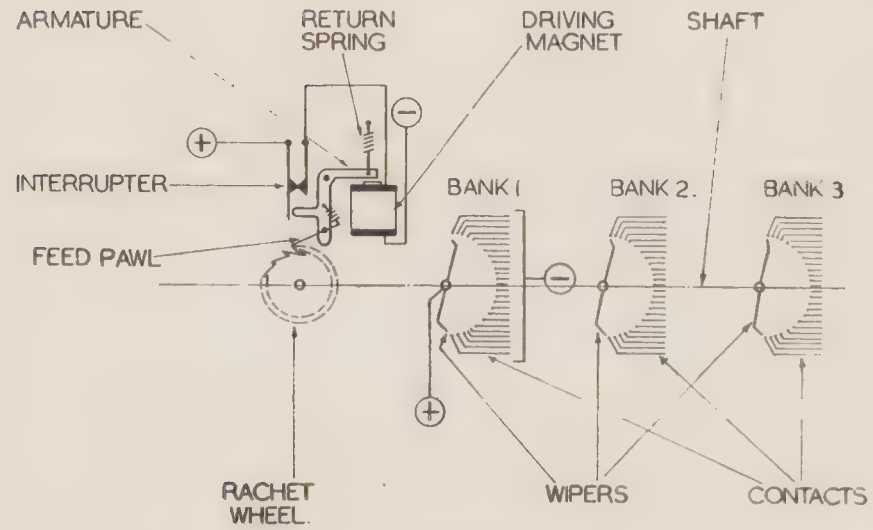


FIG. 16-17.—*Uniselector Circuit.*

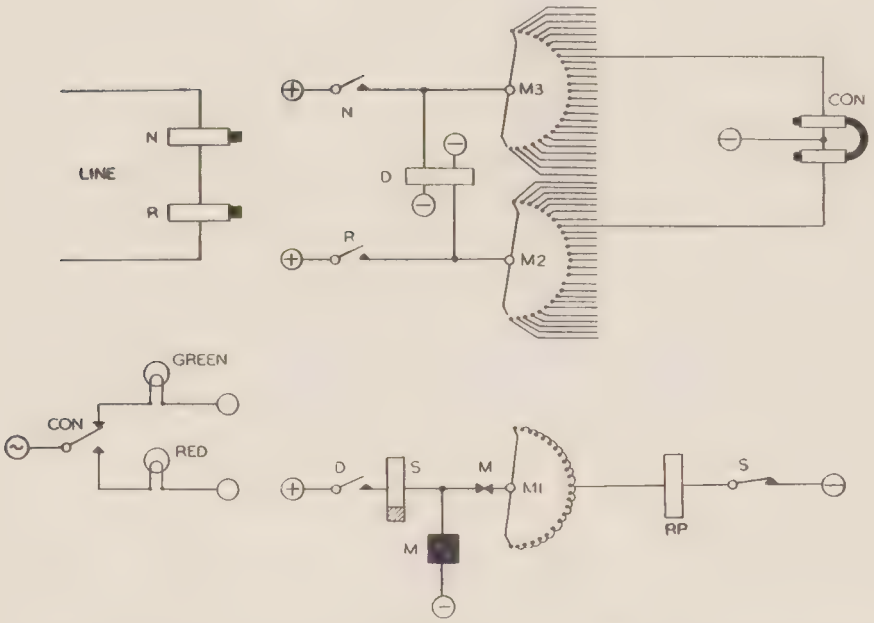


FIG. 16-18.—*Uniselector Circuit for indication of positions of remote controlled circuit-breakers (The Automatic Telephone and Electric Co., Ltd.).*

The application of a uniselector switch to a supervisory control scheme is shown in Fig. 16-18: a typical circuit for indicating the positions of twenty-five circuit-breakers or other switching equipment. When it is desired to check the positions of the breakers, or alternatively, if one of them opens automatically, twenty-five impulses, each of which corresponds to a particular breaker, are transmitted to the control room.

According to the positions of the circuit-breakers, the impulses will be of normal or reversed polarity, and each impulse will operate one of the polarised relays N or R. This in turn energises one or other of the windings of the polarised relay CON, one of these relays being associated with each circuit-breaker. The CON relays operate and release when one or the other winding is energised and are arranged to control the supply to the red and green lamps associated with the circuit-breakers.

The function of the uniselector is to associate each impulse received from the substation with the appropriate CON relay. Each time one of the polarised relays N or R pulses, the driving relay D will be operated by one or other of its windings. This in turn will cause impulses to be connected to the uniselector operating coil of the magnet M in series with the slow-acting relay S, which remains in the " Operated " position during the period between one operation and the next.

By this means, the uniselector is rotated step by step and the appropriate CON relay is energised via one of the levels M2 or M3 according to which of the polarised relays operates.

It will be noted that while the impulses are being received, the contacts of relay S remain open, thereby disconnecting the self-drive circuit of the uniselector operating magnet.

Normally, when twenty-five impulses have been transmitted, the uniselector will finish at its initial position, having completed half a revolution, and the restoration of the self-drive circuit at this stage will have no effect. If for some reason however, such as a line fault or transient, the equipment does not receive twenty-five impulses, and consequently does not come to rest in the home position, the restoration of relay S will cause a circuit to be established for the operating magnet in series with the coil of relay RP wiper, M1 and the interrupter contacts. This will cause the uniselector to return to contact 1 and by means not shown in the diagram, the relay RP will cause the impulse train from the substation to be repeated until the correct results are achieved. This eliminates the possibility of incorrect indications.

Control Room Equipments.

Where a supply network covers a large area, and includes very many substations all controlled from a central control room, wall diagrams are included as part of the supervisory control equipment. Not only is this an advantage in that it gives the control engineer a complete view of the switching conditions existing on the network, but it also enables the control desk or main control panel to be kept as small as possible with the minimum number of controls.

A section of a typical wall diagram for a large city network is shown in Fig. 16-19. This diagram is 30 feet long, and 11 feet high and comprises some 234 panels, each 10″ × 10″ on which are mounted automatic semaphore indicators incorporating miniature lamps, etc. Each small panel is manufactured and " lined " independently and accurately, being afterwards carefully fitted " *in situ.*"

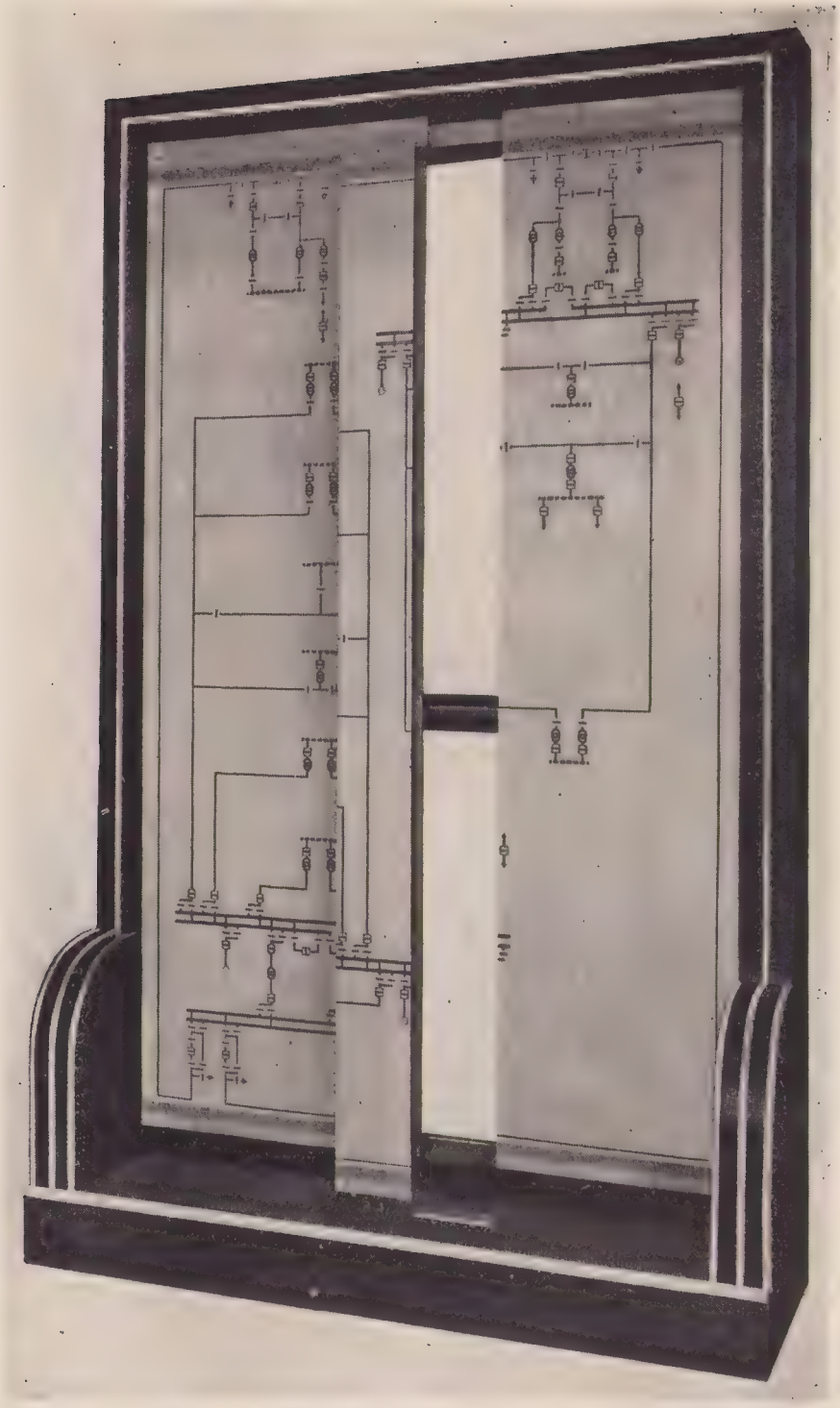


FIG. 16-21.—*Complete Mosaic Type Wall Diagram with one section removed to show the ease with which alterations may be made (The Automatic Telephone and Electric Co., Ltd.).*

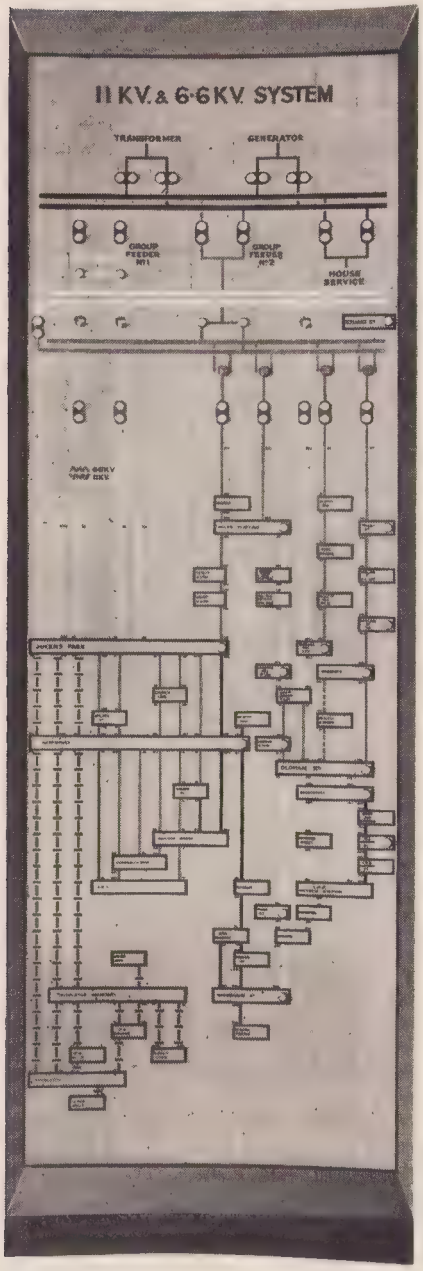


FIG. 16-22.—*Wall Diagram of "Tile" Construction (Standard Telephones and Cables, Ltd.).*

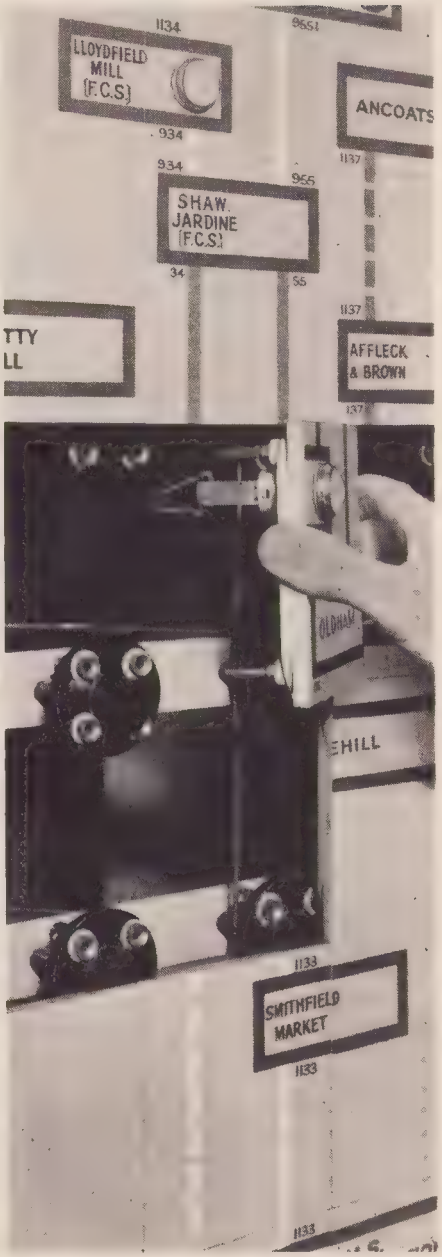


FIG. 16-23.—*"Close-up" of Section of Fig. 16-22 with tiles removed to show method of fixing (Standard Telephones and Cables, Ltd.).*

$4\frac{1}{2}'' \times 3\frac{3}{4}''$. The tiles are located by plugs inserted into sockets in the frame as shown in Fig. 16-23, and these also furnish connections for the lamp circuits. A maximum of three lamps can be provided for each tile, with a choice of six positions, and for this purpose, " knock-outs " are provided in the tiles. It is, therefore, only necessary to stock a number of tiles of one type, together with indication lamps and coloured tapes, in order to provide for modifications and future extensions to the diagram.

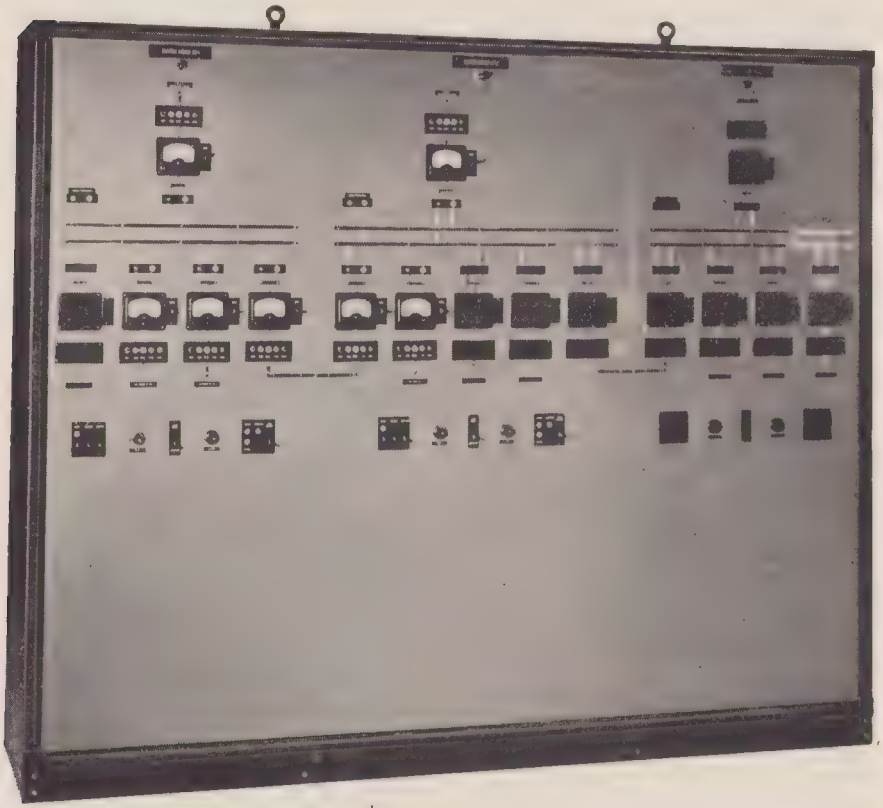


FIG. 16-24.—*Supervisory Control Board for Voice Frequency Signalling System with provision for future extensions (The General Electric Co., Ltd.).*

Supervisory control units may be grouped upon control panels or desks as desired, according to the layout of the control station. For single switchboards or for small distribution systems, all necessary controls, indication signals, and instruments are usually accommodated on single panels as shown in Figs. 16-1 and 16-10, but in the case of larger and more complex installations, control boards of unit construction are generally employed.

Control desks incorporating miniature apparatus of special design and miniature diagrams using new light techniques offer advantages in that a multiplicity of control facilities can be catered for in a small compass with

a particularly convenient disposition of apparatus, all tending towards more efficient operation. It will be observed that the use of control desks enables unobstructed views across the substation to be obtained, and this is of particular importance when wall diagrams are provided.

The modern trend is to limit control room equipment to the essential operating panels only, and accommodate the associated apparatus in nearby relay rooms, the interconnections being made by means of small gauge multicore cables.

Control panels are generally of sheet steel construction, though aluminium alloys provide an interesting alternative. Desks, however, are not infrequently of part wood and part steel construction. The metal portions of panels and desks may be finished in a variety of colours, *e.g.*, grey, black and eau-de-nil. The latter is very popular since it is a colour which is restful to the eye. The single line diagram provided is usually sign painted, although metal strip diagrams are often used as shown in Fig. 16-24. Control keys and semaphore indicators are incorporated in the line diagram to represent the circuit-breakers, isolators, etc. Alarm indicators and keys are generally segregated from the diagram, partly for convenience and partly in order to restrict the size of the diagram. Fig. 16-25 shows a typical control desk where the station alarm indicators are mounted towards the rear of the control panel, to assist the operator in noting quickly the origin of the alarm.

The illustration Fig. 16-26 shows a view of the control room for a large electric railway traction system. The large control panel in the background is semi-circular in shape and gives indication, etc. for the 1,500 volt system. In the foreground is the control desk and the engineer's desk. This equipment gives control of 28 substations and the attractive layout is worthy of note.

Substation Equipment.

With a simple direct wire control scheme, it is possible under some circumstances to fit the supervisory control equipment on the switchgear, either within the instrument panels as has been mentioned earlier, or within the control and relay panels if these are provided. However, when the necessary equipment assumes sizable proportions, it must be mounted separately. Pressed steel cubicles are increasingly used for this purpose, and represent best modern practice. Special precautions must be taken in the design of the cubicles, and the equipment contained therein, since working conditions are often much more severe in switching stations than they are in rooms in which telephone equipment is normally housed. Dust-tight doors with rubber insertions are therefore provided and if necessary, local heaters or air drying units are incorporated for very humid atmospheres.

The items of equipment housed inside the cubicles are mounted on small "jack-in" panels as shown in Fig. 16-27. This facilitates removal for cleaning, maintenance, testing or replacement.

Examples of wall and floor mounting apparatus cabinets are shown in Figs. 16-28 and 16-29 respectively, and the attention paid to terminal arrangements will be noted.

Testing Facilities.

It is clear that to ensure constant reliability in operation some provision must be made for maintenance testing. Only by this means is it possible to detect and correct adjustments, which if not attended to might result in

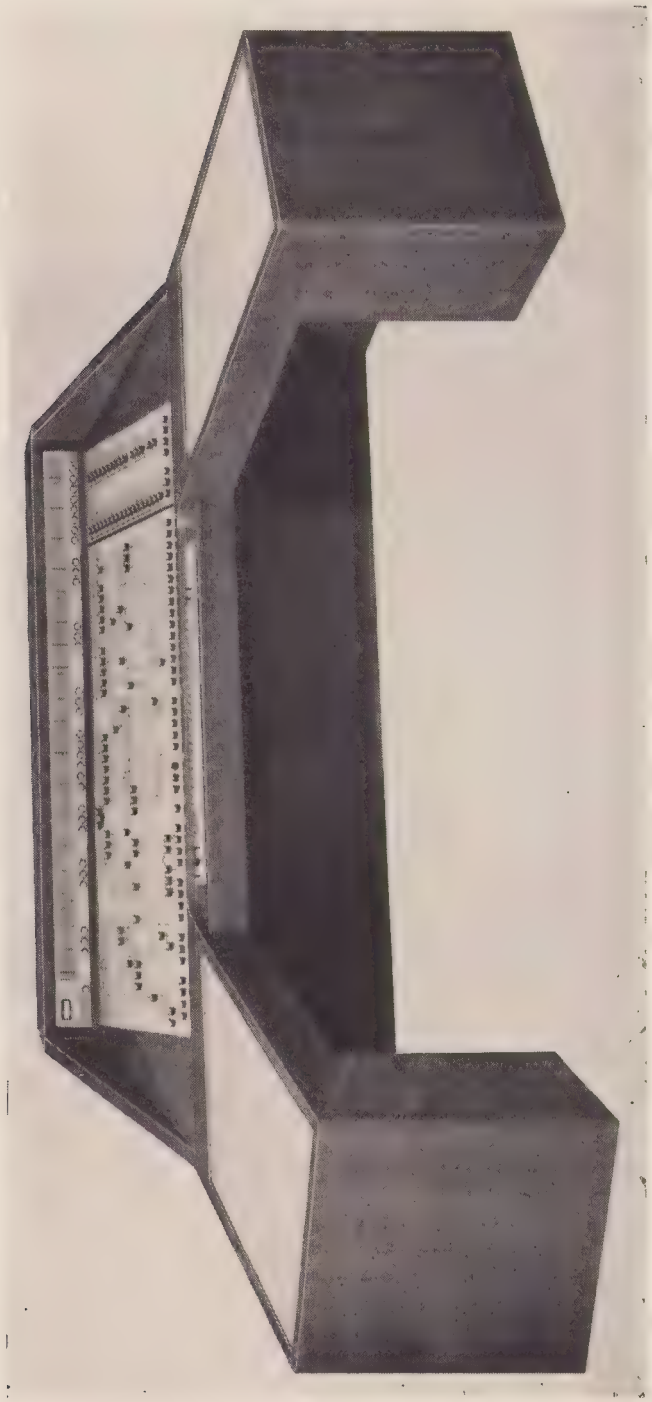


FIG. 16-25.—*Control Desk for Large City Network (Standard Telephones and Cables, Ltd.).*

FIG. 16-26.—*Control Room for large Electric Railway Traction System, showing semi-circular System Diagram with Control Desk and Engineers' Desk in the foreground (The General Electric Co., Ltd.).*

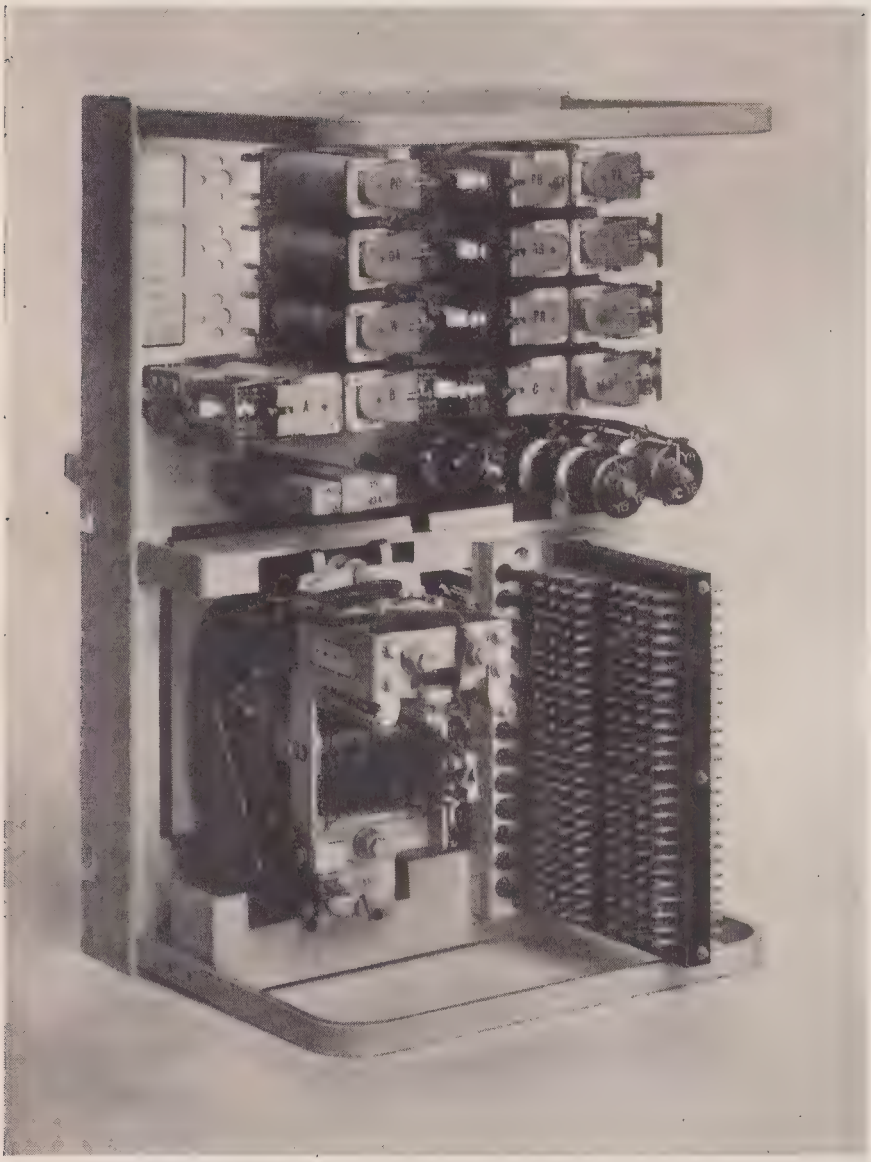


FIG. 16-27.—*" Jack-in " Type Apparatus Panel (Standard Telephones and Cables, Ltd.).*

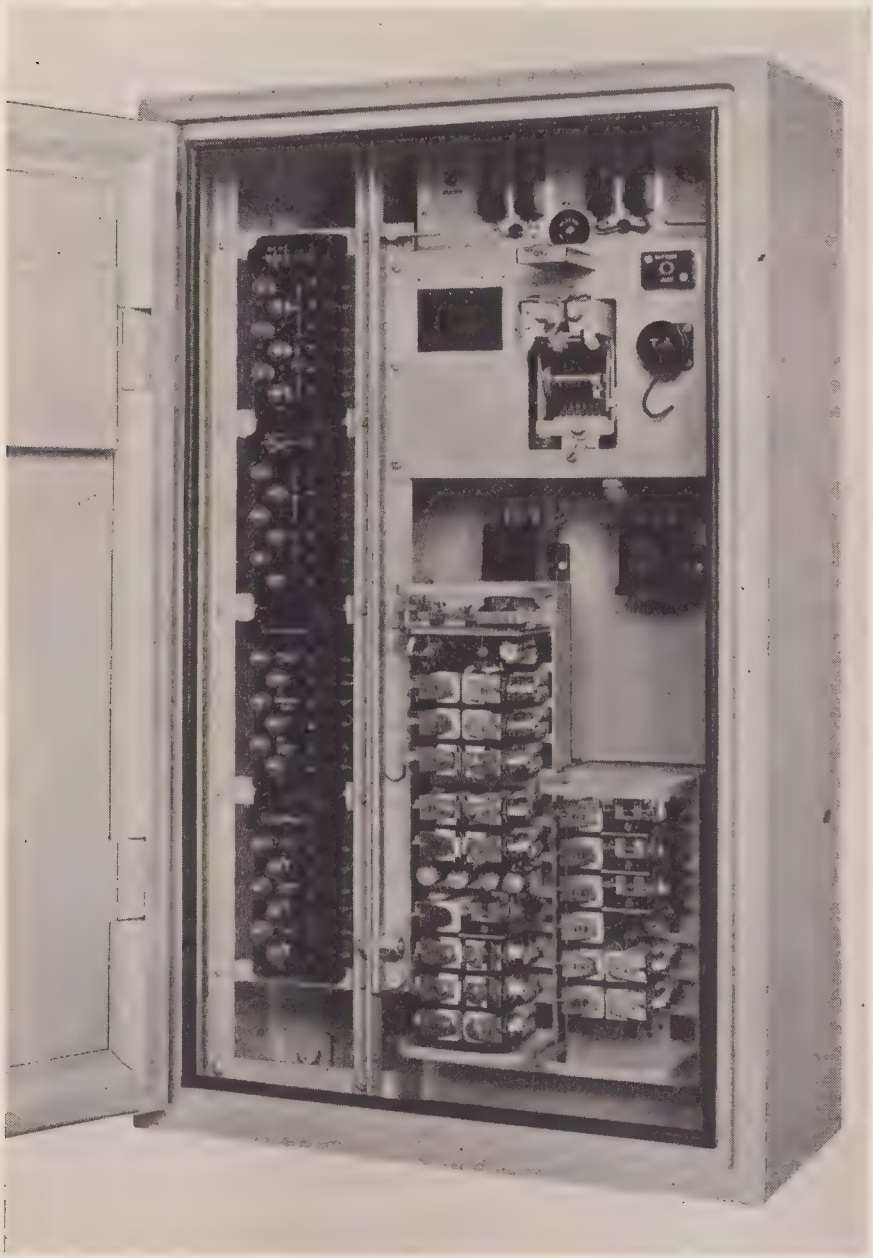


FIG. 16-28.—*Wall-mounting Apparatus Cubicle with door open showing "Jack-in" Apparatus Panels as illustrated in Fig. 16-27 (Standard Telephones and Cables, Ltd.).*

FIG. 16-29.—*Floor-Mounting Apparatus Cubicles for Voice Frequency Signalling System (The General Electric Co., Ltd.).*

failure of operation. The amount of attention which has to be given to the equipment must depend to a degree upon the conditions under which it has to operate, as well as upon the frequency of operation. Consideration must also be given to the pilot lines.

Portable testing sets are available, and these are generally supplied in pairs, one for the control station to simulate the substation signalling equipment and one for the remote substations to simulate the control station apparatus. A typical testing set pair is illustrated in Fig. 16-30, these being designed for use with the coded signalling systems described earlier.

FIG. 16-30.—*Routine Testing Sets (Standard Telephones and Cables, Ltd.).*

It will be noted that a flexible lead, and multi-way jack-plug is provided for insertion into appropriate jacks on the apparatus units at the respective locations.

Testing facilities can, if desired, be incorporated as a permanent feature in the supervisory control scheme and the comparatively small increase in initial expenditure is well justified.

It is the general practice to embody a "Check" key feature in all equipments. This "Check" key enables engineers in the control room to initiate a full cycle of supervisory indications, meter readings, etc., at any time. The whole of the apparatus may thus be exercised and checked in about a minute or so and as often as desired.

In a recent installation by one manufacturer, arrangements have been made so that by a single operation at the control centre, the selected substation supervisory apparatus can be switched from the switchgear units

normally controlled and indicated to dummy apparatus which can be operated in a very similar manner. Routine controls on, and back indications from this dummy apparatus can then be effected at will to prove the thorough operation of the over-all equipment, whereupon the equipment can be switched back to normal working conditions.

Such routine testing can be carried out by the control operators themselves—as distinct from the maintenance or servicing attendants—during a quiet period each week, thus adding appreciably to the confidence of the operator in the subsequent daily use of the equipment.

Common Diagram System.

Where it is necessary to control a large number of substations from a single control room, it will be appreciated that a large floor area would be required if each feeder is to be represented complete with controls and means of indication on orthodox lines. One very large panel could be used, but this might lead to difficulties in operation. Another alternative would be to split the system diagrams into smaller panels, with a large wall diagram. These alternatives have obvious attendant disadvantages. In any case, it is clear that a fairly large staff would be required for the supervision of this equipment, and under these conditions it would not be an easy matter to correlate the switching operations being carried out on the system. It should be noted that on most networks both regional and urban, constant change is in progress materially affecting any mimic diagram provided for centralised control. To keep the normal factory-made diagram up-to-date may, therefore, prove quite impracticable, and resort must be had to means whereby complete system representation in diagrammatic form is perserved, and at the same time the switching forms in detail at each substation can be reproduced at will. The Common Diagram System employing one fairly small control panel under the supervison of one operator in conjunction with a system diagram provides a ready and economically attractive solution to such problems.

When the substation plant arrangements for a distribution network are reviewed, it is found that the least common multiple of equipment is not larger than the ultimate largest of any substation provided on the network. This is reasonably easy to state, since for reasons of economy and also of load distribution and voltage drop, it is not good policy to permit the unlimited growth of a single substation, however great the load density may be. Thus a least common multiple of remote supervisory control equipment can be designed for any group of substations.

Clearly, for the satisfactory operation of a common diagram system, facilities must be provided for switching pairs of pilot wires to make them available to the common equipment, one pair at any one time. Further, the equipment must be so set that for a period of time it loses its least common multiple character, and assumes that of the particular substation.

In addition to providing a common diagram for a system, feeders and transformers, etc. must bear identity numbers and means to display them. Numbers must be provided, too, for the various substations in order to derive full benefit from the flexibility of the common diagram system. Facilities must also be included to display the identity numbers of more than one substation which is occupying the common diagram. Apart from the lamp indication on the system diagram of all the substations reporting trouble, there should be means to display the identity of substations occupying or requiring to occupy the common diagram.

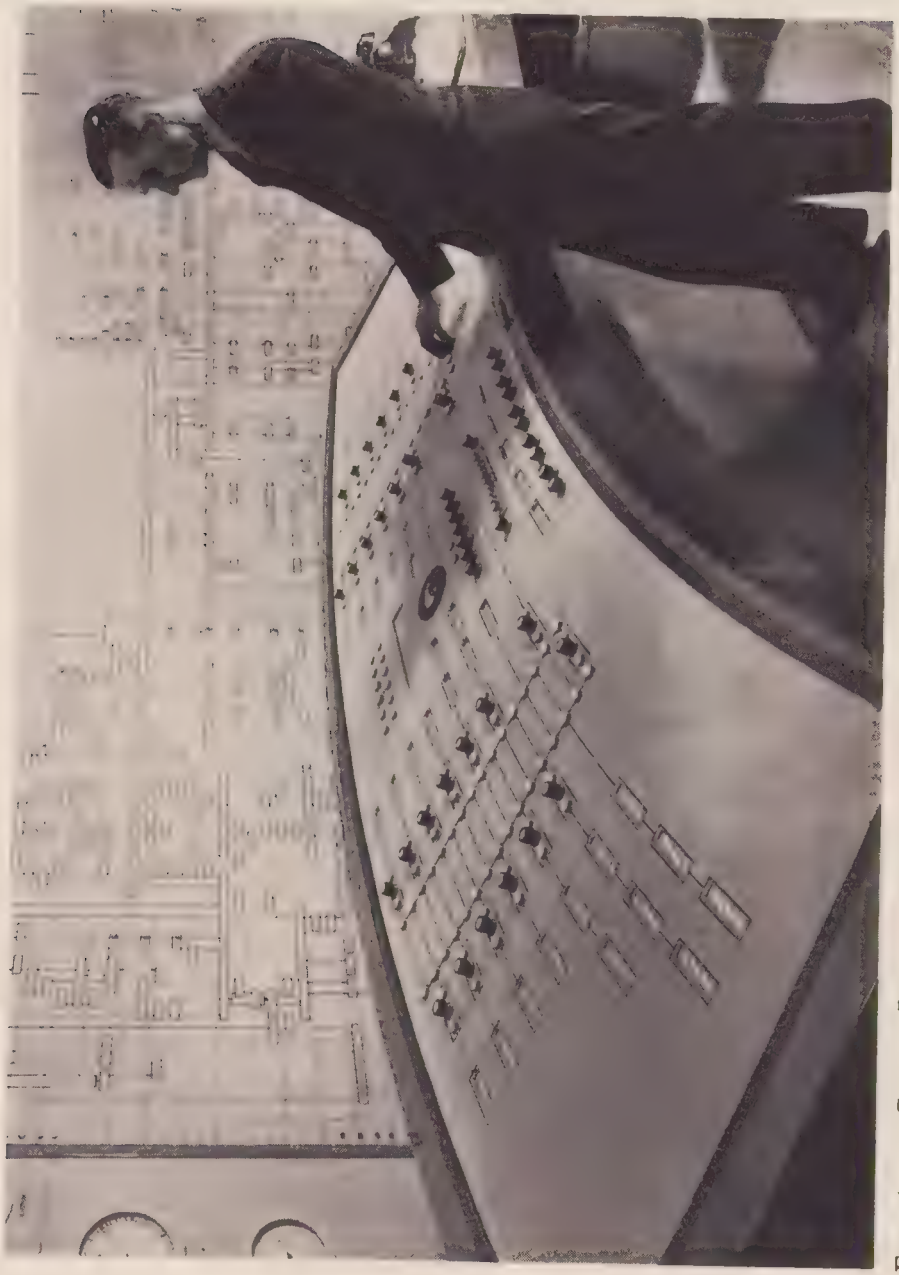


FIG. 16-31.—*Common Diagram System Control Desk showing Line Diagram, Control Keys, Indication Lamps and Designation Indicators, etc.* (*Standard Telephones and Cables, Ltd.*).

It has been found in practice that economy in pilot lines can be effected by grouping the substations around radiation points so that only a single pair line between each substation radiation point or tandem and the control station is required.

The Common Diagram System for a large city network employs a wall diagram similar to that described on page 350. On this it is possible to signal individually any stations reporting trouble and for a system fault involving a number of stations a complete view of the affected area can be obtained. The common diagram desk is provided with a suitable line diagram as shown in the example Fig. 16-31 which incorporates facilities for double busbar switchgear. Control keys, check keys, etc. and means of indication described earlier are included. Metering and multi-position devices such as transformer tap indicators may be provided together with an alarm display panel to give indication of the operation of buchholz devices, earth fault protection, fire detection equipment, etc.

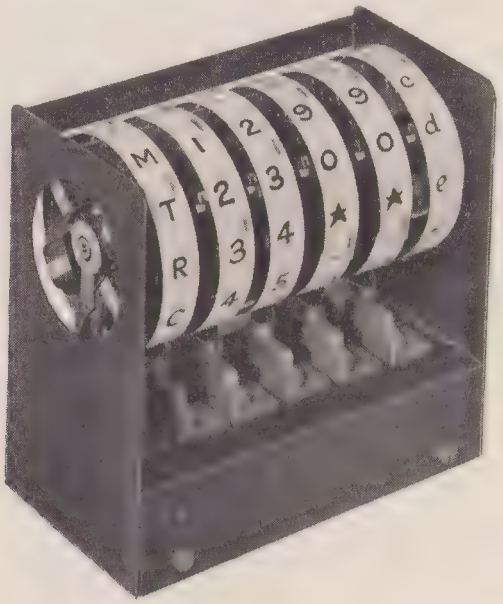


FIG. 16-32.—*Digit Wheel Indicator* (*Standard Telephones and Cables, Ltd.*).

To indicate the name or number of the feeder, transformer, etc. on the control desk, beside the appropriate key or lamp, digit wheel indicators are used. These are similar in appearance to the familiar "Veeder" indicator, but are electrically operated, being arranged so that all the wheels can be operated simultaneously and independently to any required position. A typical digit wheel indicator is shown in Fig. 16-32.

A simple diagrammatic representation of a common diagram system is given in Fig. 16-33, which shows part of the power network, and a tandem station, together with the wall diagram, and common diagram. It will be seen from inspection that it is possible to represent any of the substations shown in the power network diagram on the common diagram panel.

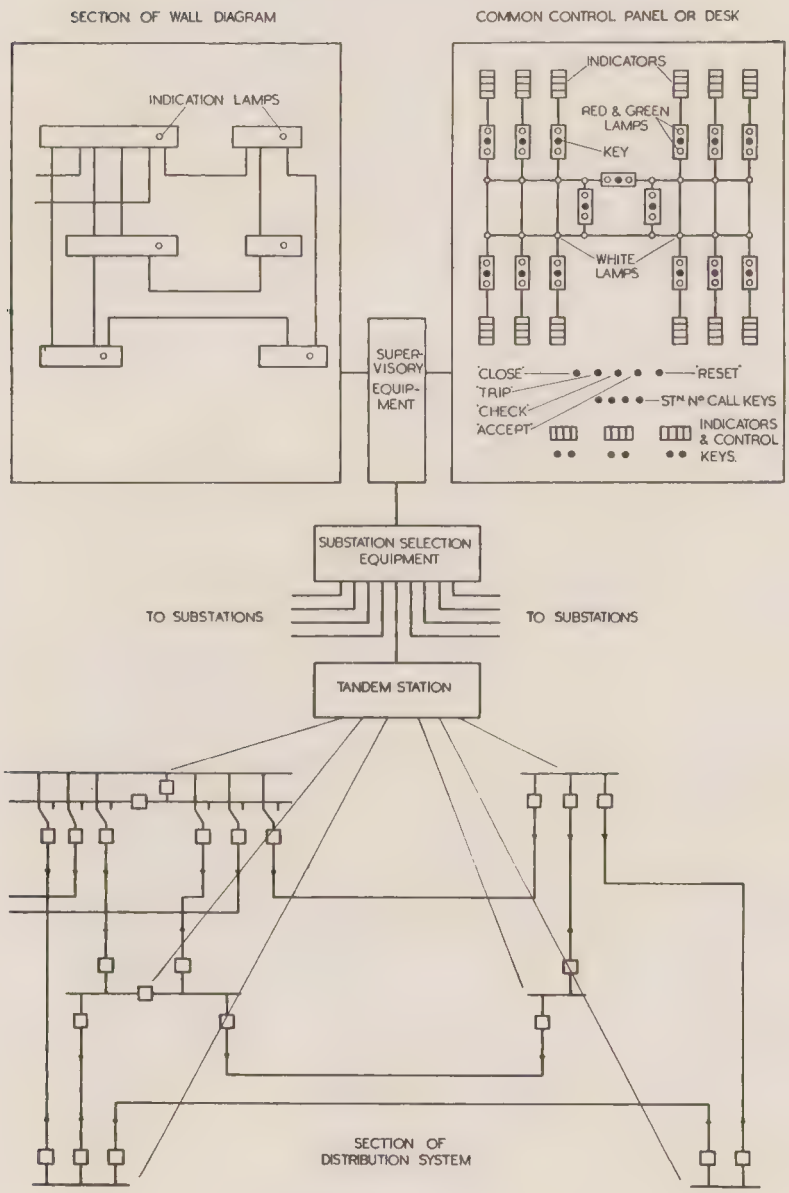


FIG. 16-33.—*Block Schematic of Common Diagram System.*

FIG. 16-34.—*Control Room for Large City Network, employing Common Diagram System, showing Common Diagram Control Desk, with Wall Diagram in the background (Standard Telephones and Cables, Ltd.).*

To associate the common diagram with any given substation preparatory to checking that station, the control engineer selects the substation by number and so automatically dresses the diagram, *i.e.*, the diagram indicators are set to give the names or code letters of all the breakers. He then sends a check signal to the particular substation via tandem, whereupon signals

FIG. 16-35.—*Control Desk for Electric Railway Traction System employing Common Diagram System (Standard Telephones and Cables, Ltd.)*

are returned to the control room giving information of the position of all breakers, alarms, etc. This information is registered on the diagram by the lighting of red and green lamps for " Close " and " Open " respectively, together with the position " Front " or " Rear " busbars of all busbar selection switches.

If it is now necessary to operate a circuit-breaker, the selection key mounted adjacent to the red and green lamps indicating the particular

circuit-breaker, is actuated. This action sends a signal to the substation again, and the circuit-breaker control circuit is selected, whereupon a signal is returned to the control station, causing the light on the selection key to flicker, and the "Close" and "Open" keys common to the panel light up red or green. The "Close" (or "Open") key is now operated according to requirements, and the red (or green) lamp lights up to show when the operation has been successfully carried out.

If a station signals automatically, for instance through a fault on the system, the appropriate lamp on the diagram is illuminated. This lamp flashes until the number of the substation is displayed on the common diagram control-panel, when it changes to a steady light, thus informing the control engineer of the fact. Provision is made so that the numbers of several substations may be automatically displayed at the same time, and it is possible to select any one of these stations according to their importance by the operation of the keys fitted adjacent to the digit wheel indicators.

Fig. 16-34 shows one view of a control room serving a large city network and equipped with the Common Diagram System of supervisory control generally on the lines just outlined. In this instance the number of substations connected totals approximately 100, but the scheme is planned to cover ultimately a total of more than 400 substations. Part of the 6·6 kV and 11 kV wall diagrams can be seen in the illustration with the circular shaped desk with two writing positions and central diagram panel in the forefront.

Another interesting application of the use of the common diagram system concerns the centralised control of a number of rectifier substations serving a suburban electrified line in the London area. One view of the control equipment is shown in Fig. 16-35. In this case an illuminated single line mimic diagram of the network forms the rear of thetdesk, which is fitted with duplicate common control panels for the use of two operators, either of whom has access to all remote stations. The two conrol panels are separated by a set-up, designation panel which mounts keys in rows per substation for lighting the appropriate lamps on the mimic diagram in accordance with the information received on the flanking master panels. This designation panel also carries on the keys the relative code designation and number of each one of the breakers incorporated in the scheme.

Supervisory Remote Control Equipment for the Galloway Water Power Scheme.

This installation provides an interesting example of the application of supervisory remote control, since it caters not only for the necessary switchgear, but also for the control of water power.

The power scheme involving a catchment area of 400 square miles for its water power, comprises the following generating stations: Kendoon, Carsfad, Earlstoun, Glenlee and Tongland, which together have a total plant capacity of some 100 MW. Of these five substations, Earlstoun and Carsfad are unattended and controlled from Glenlee.

The supervisory equipment installed provides facilities for the remote control and indication of intake gates, remote indication of water level and flow at each generating station, with the exception of the two unattended stations. The facilities provided for the latter include the remote control and indication of automatic control equipment for each alternator, control of alternator field rheostat and voltage regulator rheostat as well as the control

FIG. 16-36.—*South East England area of "Grid," showing network existing when Centralised Supervisory Control Equipment was commissioned.*

and indication of transformer tap changing gear. In addition, indication is provided for h.v. and l.v. circuit-breakers, meter readings for alternators, station battery, etc. and water level indication. The alarms which are included cover alternator temperature, outlet air, bearing oil pump and change of position of intake gates associated with turbines.

It is worthy of note that under emergency conditions, the Glenlee station can be brought into service and run up to feed into the " Grid " in less than ten minutes.

Centralised Supervisory and Metering Equipment for the South East Section of the English " Grid System."

As a further illustration of the application of supervisory control, the centralised supervisory and metering equipment for the South East Section of the " Grid " scheme has been selected, and Fig. 16-36 shows the large area that is served. Originally the central control station was centred at Bankside, which is situated on the south side of the Thames about midway between Battersea and Deptford. During the war years, all the equipment was moved underground into a liftshaft at St. Pauls Station so that control could be maintained during heavy bombing. The illustrations and descriptions included here, however, are confined to the original Bankside station.

The supervisory equipment included in this scheme provides the following remote indicating and signalling facilities for the various substations throughout the area :—

(1) Continuous indication of the " Closed " or " Open " positions of each distant breaker.

(2) Both-way telephonic communication between Bankside control and each distant station.

(3) Continuous indication of the particular tap in use on each distant transformer.

(4) The indication of summated MW and reactive MVA loading of the main " Grid " transformers, and on main, intersection and inter-area feeders; also the total loads on the generating stations. The metering indications for the main " Grid " transformers are so arranged as to be transmitted automatically as required upon receipt of a signal from the central control station. The remaining metering indications are given continuously, except that they are subject to interruptions by telephonic communications.

(5) Continuous indication of the supply frequency which is arranged to be transmitted from one substation in each of the four subsections of the area.

In addition, the central indicating station has remote control of the following operations at certain of the distant substations :—

(a) The transmission of one of any seven specific operating instructions to each generating station and the acknowledgment by the station concerned of the receipt of the particular instruction transmitted.

(b) The automatic tripping of certain circuit-breakers in accordance with the signals transmitted from central control station.

FIG. 16-37.—*View of Bankside (C.E.B.) Control Station, showing large Mosaic Type Wall Diagram with smaller Area Diagrams and Wall Map. In the foreground are the Engineers' desks.*
(The Automatic Telephone and Electric Co., Ltd.).

The control room at Bankside shown in Fig. 16-37, is circular, and on one side is the system wall diagram together with the area diagrams. In front of this are the engineers' desks. The main indicator board is situated against the opposite wall and gives details of loading, etc. of the various substations under supervision. Immediately facing these panels is situated the loading desk shown in Fig. 16-38. The position of the latter in relation to the main indicator board, is such that the control engineers have an unimpeded view of all the indicating panels, one of which is provided for each of the distant stations or substations.

Ceiling lighting is provided in the control room, and the main indicator board is illuminated from duplicate flood lighting equipment arranged along the floor of the well in the loading desk. The floor of the room is covered with coloured linoleum, and all wooden fittings are of polished mahogany.

A local automatic telephone exchange is included for communication with remote stations under supervision.

The system wall diagram is of the mosaic type described on page 350 and illustrated in Figs. 16-20 and 16-21. It is of interest to note that this diagram comprises a total of 55,000 one inch squares arranged in vertical strips 6" wide. Each strip can be readily withdrawn for the purpose of quickly re-arranging the diagram to conform with any changes that may have been made in the network.

The main indicator board shown in Fig. 16-38 comprises a number of panels, one for each of the stations controlled from Bankside. The top sections of these panels are fitted with the transformer tap position indicators and metering receiving instruments. At the bottom of the panels are lamps indicating the conditions of general alarm, channel engaged signal and reactive MVA metering signal. The centre sections carry diagrams showing the arrangement of feeders on the station busbars, all feeders and symbols being coloured to indicate the particular voltage. In line with each feeder is a lamp indicator of the type described earlier, arranged so that the position of the associated breaker is indicated by steady illumination, either red or green. The diagram also includes rotary-type plungers representing busbar isolating switches which can be set by hand to correspond with the actual prevailing connections to the busbars of each feeder. On the lower panels are the operating keys for each station. A combined "Check" selection and alarm reset key, with lamp, is also provided. In addition, certain services have a key for obtaining reactive MVA metering indications.

The loading desk accommodates two control engineers, and both have access to the centrally located routine instructions panel. The latter incorporates four transmitters, one for each of the sub-sections of the complete area, and these enable instructions in connection with the loading conditions to be sent. Provision is also made for the remote tripping of certain distant circuit-breakers, and the necessary keys are arranged for locking to prevent inadvertent operation.

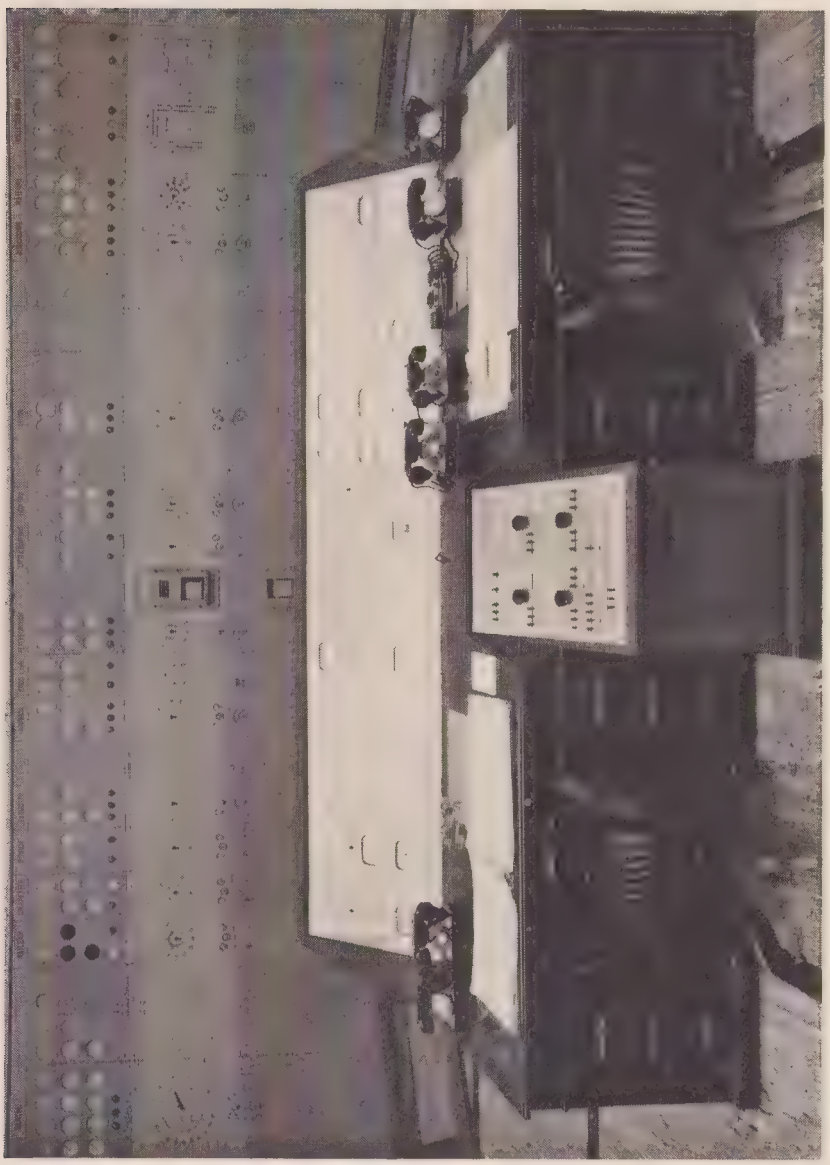


FIG. 16-38.—*Loading Desk at Bankside (C.E.B.) Control Station, showing Instrument Panel and small Routine Instruction Panel. The Main Indicator Board with Line Diagrams, Instruments and Controls for the various Stations is situated in the background (The Automatic Telephone and Electric Co., Ltd.).*

ACKNOWLEDGMENTS

Figure 16-26 was published by permission of the London Midland and Scottish Railways, Figs. 16-31 and 16-34 by permission of Manchester Corporation Electricity Department and Figs. 16-37 and 16-38 by permission of the Central Electricity Board.

BIBLIOGRAPHY.

" Remote Control," C. Gordon White, " British Engineering Export Journal," March and April, 1946.

" Operational Control of Electric Supply Systems," W. Kidd and E. M. S. McWhirter, " Journal I.E.E.," 1945, Vol. 92 (part 2), p. 311.

" Supervisory Remote Control Equipment for the Galloway Power Scheme," J. H. Moles, " Strowger Journal," November, 1937.

" Centralised Supervisory and Metering Equipment for the South East Section of the English Grid System," J. J. Ferguson, " Strowger Journal," December, 1938.

CHAPTER XVII

BUSBARS AND CONNECTIONS*

Two commercial materials are most suitable for conductor purposes in switchgear construction, *i.e.*, copper and aluminium. Silver has better properties than either of these but its cost makes its use prohibitive. The following table indicates the relative properties of copper and aluminium.

	Copper	Aluminium
Weight per unit length for equal conductivity	1·0	0·50
Conductivity for equal areas :—		
Electrical	1·0	0·61
Thermal	1·0	0·56
Tensile Strength (Hard drawn)	1·0	0·40
Hardness (Hard drawn)	1·0	0·44
Modulus of Elasticity	1·0	0·55
Co-efficient of Thermal Expansion ..	1·0	1·39
Melting Point	1·0	0·61

It will be apparent that for equal conductivity aluminium has an advantage in weight. The latter is not usually important to any degree in switchboard work, the more important consideration being space. In consequence, much greater use is made of copper than aluminium.

Copper.

Copper for use as busbars or conductors must be of the highest purity. That described as " high conductivity " should have a total content of impurities, including oxygen, less the 0·1%. Standards have been laid down by the International Electrotechnical Commission and these have been adopted as British Standards. Hard drawn, or medium hard drawn, copper, on account of its greater stiffness and strength, and its better surface finish, is preferable to the use of annealed copper. While surface finish is important, greater importance is attached to dimensions. These are specified within close limits—plus or minus 2% on thickness and plus or minus 1% on width for flat bar. These close limits enable switch blades to be made from bar as received without machining.

Current Carrying Capacity.

It can be shown that no fixed density can be specified for busbars or connections. The old rule of 1,000 amperes per square inch is entirely wrong and the carrying capacity of a given cross-section of bar is decided by the temperature rise due to the current to be carried. The heating

**The permission of The Copper Development Association to quote from its publication No. 22 " Copper for Busbars " is gratefully acknowledged.*

depends on a number of widely varying factors, such as number and arrangement of laminations, relative size of bar, access of cooling air to conductor surface, frequency of electric supply, and thickness of covering of immersing medium. It can be shown in many cases, particularly where small bars are involved, that densities well over 1,000 amperes per square inch can be used, thus economising in copper. For insulated and immersed bars (*e.g.*, oil, compound) the number of variables is so great that each installation has to be designed individually as, for example, in compound filled switchgear where not only the compound filling itself must be considered, but also the nature and form of the surrounding metal enclosure.

For bars in the open, as in flat-back switchboards, and to a slightly lesser degree, in cubicles or truck switchgear, where air is in free contact with the bars, the conditions are sufficiently similar to enable a table of current values to be assigned as a guide to the carrying capacity to be expected.

Such a table has been included in B.S. 159. This specification also indicates the temperature limitations on which all current carrying capacities should be determined, and the current issue now gives one value, *i.e.*, a temperature rise not exceeding 50°C. with a qualification that in the neighbourhood of instrument or meter shunts, a higher value is permitted. As in the majority of problems where temperature is involved, it is the *total* temperature which is important, and as this is dependent on the ambient conditions, it is apparent that where switchgear is installed at a point where the normal ambient is high, then a lower temperature rise (involving a larger cross-section of copper) must be worked to. It is a good rule to allow that at no point should the *total* temperature exceed 80°C. and preferably this should be the very upper limit if trouble is to be avoided at joints.

The amount of heat generated in a conductor is proportional to the resistance of the conductor and to the square of the current it has to carry, while the temperature rise depends on the rate at which the heat is dissipated. The effective resistance under D.C. and A.C. conditions vary considerably, as will be shown later. Heat dissipation in either case takes place in varying degrees by convection, radiation, and conduction. This depends on a number of factors such as size, shape, whether the bar is on edge or on the flat, and whether freely exposed to the air or is surrounded by insulation, etc.

The Copper Development Association have described in some detail experimental work carried out at the National Physical Laboratory to establish the direct current carrying capacity of normally tarnished copper bars, rods and tubes. The formulæ derived from these investigations are : —

Flat Bars..	$I_{dc} = 600a^{0.5} \times p^{0.39}$
Round Bars (Solid or Hollow)..	$I_{dc} = 607a^{0.5} \times p^{0.36}$
Round Bars (Solid only) ..	$I_{dc} = 957a^{0.68}$

where I_{dc} = Direct current in amperes.
a = Cross Sectional area in square inches.
p = Perimeter of conductor in inches.

These formulæ were determined to satisfy earlier conditions in B.S. 159, *i.e.*, those where the temperature rise for bare conductors in air for currents up to 2,000 amperes was 40°C. The present temperature rise allowable is

now 50°C., and for this value, the ratings determined by using the formulæ can be multiplied by a factor 1·125. For a 30°C. rise, the factor is 0·852.

Fig. 17-1 has been produced using the formulæ above, for single bars of various thicknesses mounted on edge and freely exposed in still air. When, as is usual, a number of bars forming a laminated conductor are used, the current carrying capacity is reduced, due to reduction in loss of heat by convection and radiation. Assuming $\frac{1}{4}$ inch thick laminations and $\frac{1}{4}$ inch spacing between bars, an approximate estimate of the direct current carrying capacity can be determined by multiplying the capacity of a single bar by the following factors :—

For 2	laminations	× 1·84
,, 3	,,	× 2·52
,, 4	,,	× 3·20
,, 5	,,	× 3·88
,, 6	,,	× 4·56

Busbars and conductors for use on alternating current systems require, except in the case of very small conductors, a greater section of metal than for direct current of equal magnitude. This is due to the phenomena known as " Skin Effect " and " Proximity Effect."

Skin effect is that effect which tends to crowd the current into the outlying parts of a conductor and is due to the back EMF induced wherever an alternating flux exists by virtue of this flux cutting the conductor. This EMF is produced in a bar by its own magnetic flux and while the central portions of the conductor are cut by the flux from all parts of the bar, the outlying portions are not, the line linkages decreasing as the edges are reached. Current tends therefore to crowd into the edges of a flat strip, the outer members and edges of a multiple bar, and the skin of a circular bar, where the opposing EMF is a minimum.

Proximity effect is due to the proximity of an adjoining or adjacent pole or phase. When a bar is cut by the flux from such adjoining or adjacent conductor, the current tends to crowd into the portion of the conductor nearest the other bar. In open type switchgear where comparatively large spacings are possible, proximity effect is not so important, but where the trend is towards close-spacings as in metalclad gear, particularly of the filled type, its effect is important.

Both effects have one result—an increase in the apparent resistance of the conductors and as I^2R is the measure of the heat generated, the temperature rise of two bars of equal section carrying the same current will be higher for that bar carrying alternating current. For heavy current applications, both effects can be countered to some degree by careful consideration in the design and layout of the conductors. Skin effect, for example, can be reduced by adopting a form such as the " hollow square " or by using tubular bars. In both forms as much copper as possible is located equidistant from the magnetic centre of the bar. This is exemplified in Fig. 17-4. Proximity effect may be reduced by spacing the conductors to the maximum possible or by some special arrangement to ensure that no bar is adjacent to another.

The variations being such as to modify the effects in so many ways, and vary also with the form of the conductor, calculations can only be made

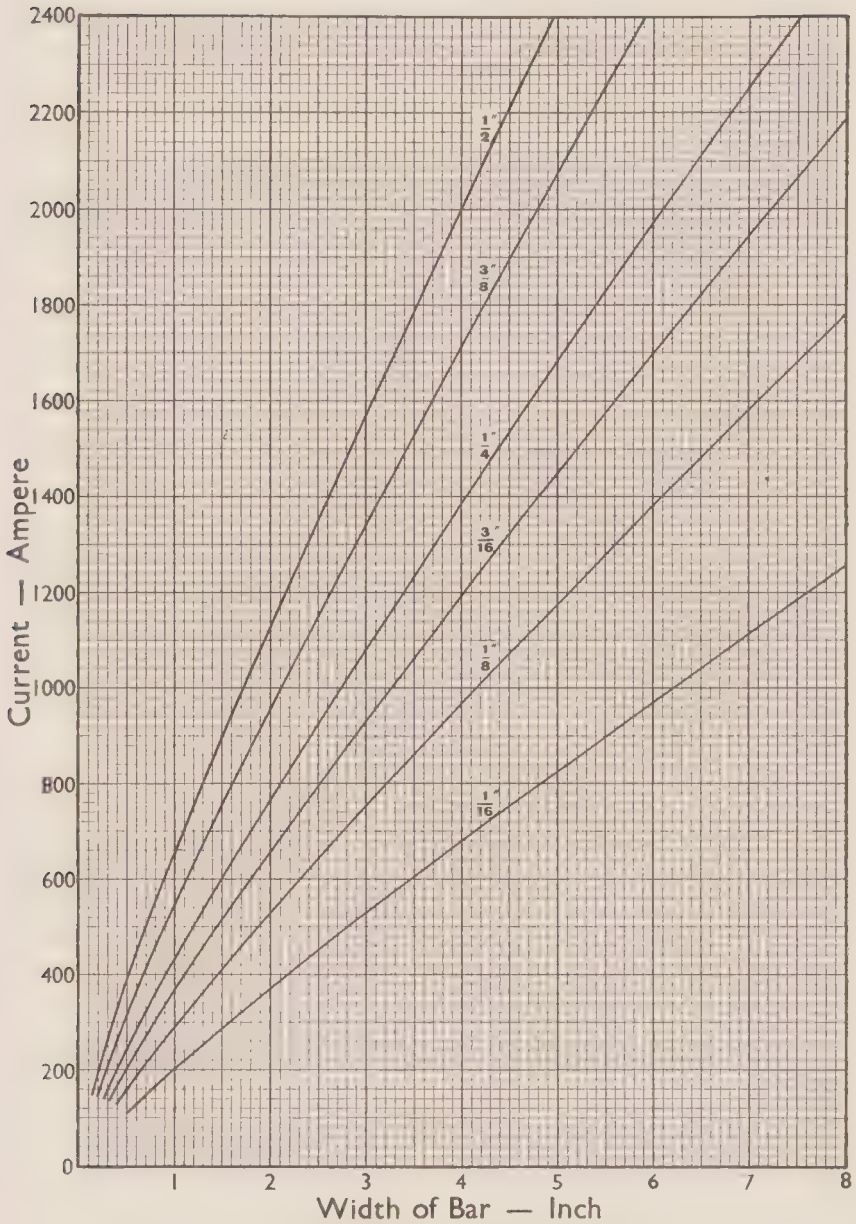


FIG. 17-1.—*D.C. Rating of flat H.C. Copper Bars mounted on edge and freely exposed in still air. Ambient Temperature, 30°C. Temperature rise, 40°C. (The Copper Development Association).*

with the aid of advanced mathematics. For flat bars, skin effect may be allowed for by use of the skin effect ratio R^1/R where

R^1 = Apparent a.c. resistance.
R = d.c. resistance.

and this ratio may be determined from Fig. 17-2. For an isolated copper conductor an approximate 50 cycle A.C. rating may be obtained from,

$$I_{AC} = \frac{I_{DC}}{\sqrt{R^1 R}}$$

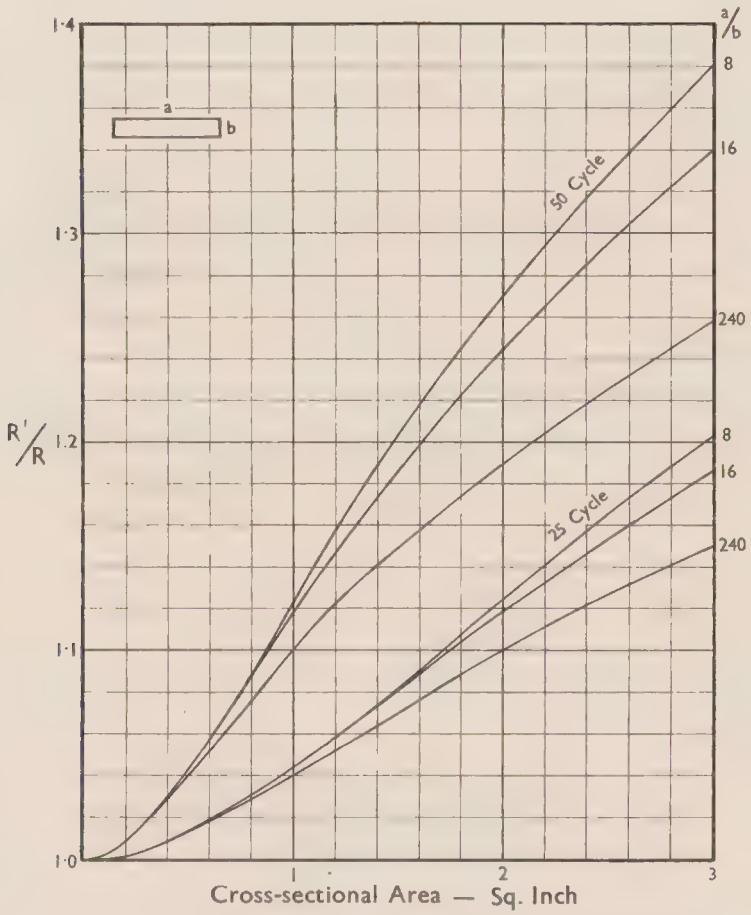


FIG. 17-2.—*Skin effect in rectangular H.C. Copper Bars (The Copper Development Association).*

taking R^1/R from Fig. 17-2, and noting that for bars having a large ratio of width to thickness the ratio is shown by the curve a/b = 240. As in the case of direct current, bars made up of a number of laminations do not carry current equal to the single bar rating multiplied by the number of bars

but some reduced proportion. The following factors apply in this case, assuming $\frac{1}{4}$ inch thick lamination spaced $\frac{1}{4}$ inch.

For	2	laminations	2	inches wide	.. 1·74
,,	2	,,	3	,, ,,	.. 1·70
,,	2	,,	4	,, ,,	.. 1·66
,,	3	,,	2	,, ,,	.. 2·30
,,	3	,,	3	,, ,,	.. 2·20
,,	3	,,	4	,, ,,	.. 2·09
,,	4	,,	3	,, ,,	.. 2·45
,,	4	,,	4	,, ,,	.. 2·30

When dealing with very heavy currents, mere increase in the number of laminations does not achieve the desired results and it becomes necessary to adopt other formations. Fig. 17-3 illustrates this point—it shows that in a bar of ten laminations, the outer strips have a density of about four times those in the centre.

Fig. 17-4 shows various alternative formations for conductors of equal cross section, in this case four square inches. The comparative current ratings are given above the columns and it will be noted that as between the first and last forms, there is a difference of 70%. This illustration is given only as a guide and should not be taken as applying in every case.

Aluminium.

The use of aluminium for switchboard work is an advantage on very heavy currents and where weight is of prime importance. The weight of an aluminium bar will be only one-half that of a copper bar for equal resistance. The economics of aluminium as compared to copper may be judged by the use for a formula given by Garrard.

$$\text{Cost of Aluminium Bar} = 0{\cdot}505 \frac{da}{dc} \times \text{Cost of Copper Bar}$$

where da = cost of aluminium per lb.
dc = cost of copper per lb.

Current Carrying Capacity.

The direct current carrying capacity of aluminium may be determined from the following formulæ :—

Flat Bars.

$$I_{dc} = kA^{0{\cdot}45} \times S^{0{\cdot}5}$$

where I_{dc} = Current in amperes.
A = Cross sectional area in sq. ins.
S = Perimeter in inches.
k = 385 for a 40°C. rise
438 for a 50°C. rise

Round Rods.

$$I_{dc} = kD^{1{\cdot}4}$$

where D = Diameter in inches.
k = 659 for a 40°C. rise.
= 749 for a 50°C. rise.

The problems of skin and proximity effects discussed for copper apply equally for aluminium.

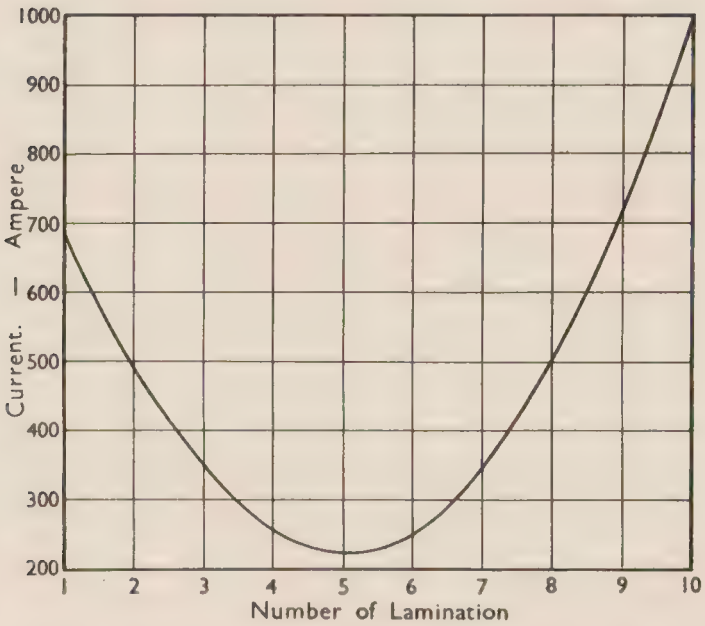


FIG. 17-3.—*Alternating Current Distribution in a bar of ten laminations* [*C. F. Wagner, "Electrical World," Vol. 79 (1922)*].

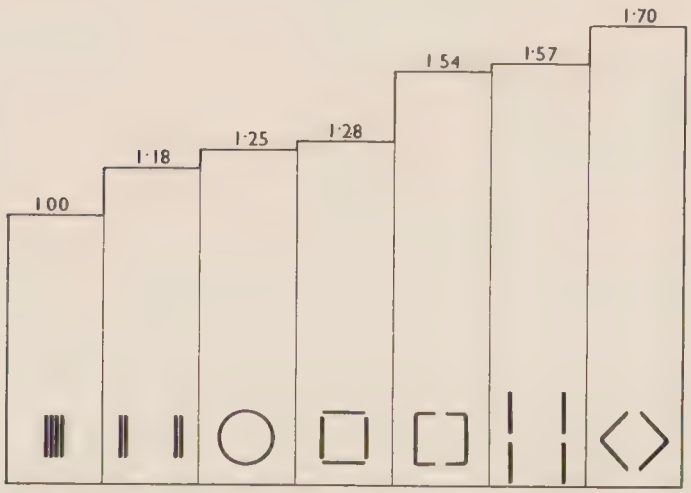


FIG. 17-4.—*Comparative A.C. Ratings of various conductor arrangements of equal cross-section, i.e., four square inches* (*The Copper Development Association*).

The factors to use for bars in parallel are given by The British Aluminium Co., as follows :—

No. of bars in parallel	Single Bar multiply by
2	1·85
3	2·55
4	3·3
5	4·0
6	4·8

assuming that the bars are on edge and are spaced apart by a distance equal to their thickness.

Short-time Rating of Copper Conductors.

Any conductor will carry a very considerable current for a short period, as when a short-circuit occurs. A conductor which has to carry fault current must clearly not attain a dangerous temperature and this is determined on the basis of the time the conductor is called upon to carry the current. The following formula may be used to determine the temperature rise per second.

$$T = k \times \left(\frac{I}{A}\right)^2 \times 10^{-8}$$

where T = Temperature rise per second degrees C.
I = Current in amperes.
A = Sectional Area of Conductor, sq. ins.
k = 1·2 for copper
2·8 for aluminium

The melting point of copper is 1,084° C. and on this basis, the smallest cross-section to carry a known current for a known time without melting may be determined from,

$$A = I \times 10^{-6} \times 5{\cdot}24 \sqrt{t}$$

where A = Sectional Area of Conductor in sq. ins.
t = Time in seconds.
I = Current in amperes.

The British Thomson-Houston Co. have published the curves shown in Fig. 17-5 for hard-drawn copper conductors, for various current densities per square inch, and showing the temperature attained in various periods of time up to 10 seconds.

The problem of conductor section on a short-time basis particularly concerns an earthing conductor. This is so often overlooked and ridiculously small conductors used on the grounds that it merely earths the system or ties the non-conducting metallic frameworks to earth.

This conductor has, however, to carry the maximum earth fault current due to the system (see typical calculations in Chapter XIII). The time during which this current can flow depends on the protective gear and the inherent clearance time of the circuit-breaker.

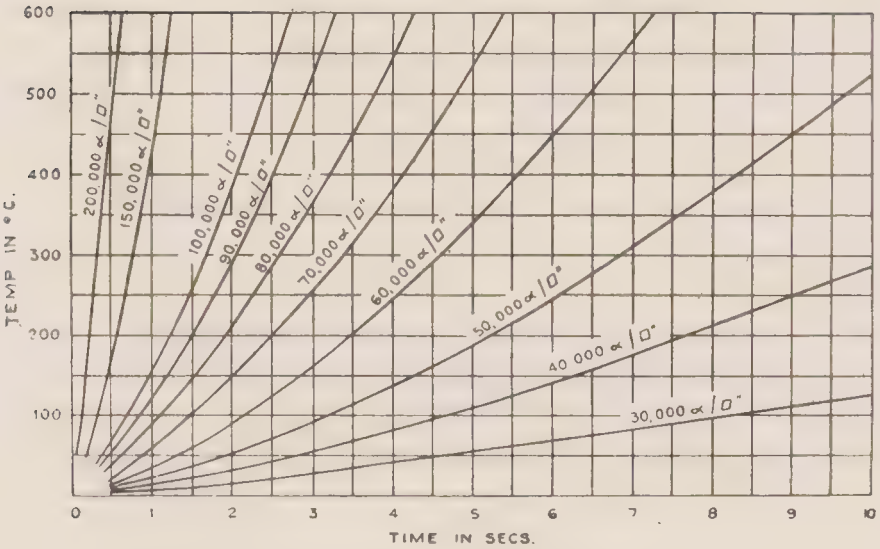


FIG. 17-5.—*Temperatures attained on short-time rating for conductors (The British Thomson-Houston Co., Ltd.).*

CLEARANCES.

Busbars and connections should be spaced in accordance with the following minimum clearance distances.

Between Phase Voltage kV	Indoor Busbars. Open or Enclosed Types. Minimum Clearance to earth in air		Minimum clearance between phases in air	
	Open	Enclosed	Open	Enclosed
	Inch	Inch	Inch	Inch
Up to and including				
0·44	$\frac{3}{4}$	$\frac{5}{8}$	1	$\frac{3}{4}$
0.66	1	$\frac{3}{4}$	$1\frac{1}{4}$	1
2·2	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{2}$
3·3	2	2	2	2
6·6	$2\frac{1}{2}$	$2\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$
11·0	3	3	5	5
22·0	$5\frac{1}{2}$	$5\frac{1}{2}$	$9\frac{1}{2}$	$9\frac{1}{2}$
33·0	$8\frac{3}{4}$	$8\frac{3}{4}$	14	14

Between Phase Voltage kV	Outdoor Busbars. Open Type	
	Minimum Clearance to Earth in Air Inches	Minimum clearance between Phases in Air Inches
6·6	6	8
11·0	7	11
22·0	9	17
33·0	13	23

The above table applies to rigid busbars only. When suspension permits swinging, these clearances must be maintained for the maximum amplitude of swing.

Between Phase Voltage kV	Busbars immersed in compound or oil	
	Minimum Clearance to earth. Inches	Minimum Clearance between phases. Inches
0·66	$\frac{1}{2}$	$\frac{1}{2}$
3·3	$\frac{1}{2}$	$\frac{3}{4}$
6·6	$\frac{3}{4}$	1
11·0	1	$1\frac{1}{2}$
22·0	$1\frac{3}{4}$	$2\frac{1}{2}$
33·0	$2\frac{1}{2}$	$3\frac{1}{2}$

Altitude has an appreciable effect on the permissible clearances and all clearances in air are intended for service at altitudes not exceeding 3,300 feet and they should be increased by 3% for each 1,000 feet in excess of 3,300 feet above sea level.

Joints.

The two essentials of a good joint are that it shall be mechanically strong and that it shall have a low resistance.

The criterion by which joints have been judged has been for long that of current density over the surface of joint. In the design of any joint the gross contact area is not of primary importance, for it has been established that current is transferred through the joint at numerous point contacts between irregularities on the contacting surfaces. It is well known that the number and effectiveness of these point contacts depends almost entirely on the pressure, and its distribution at the joint, whether by bolts or clamps. The effect of pressure on the contact resistance of a joint is demonstrated in Fig. 17-6, while the total pressures required per inch of width for joints to give 100% efficiency are given in Fig. 17-7. This, then, is the real method of judging a joint, *i.e.*, a method based on the clamping or bolting pressure. In designing to this method, however, it is essential that due regard be paid to the stresses set up in the bolts. It is usual that the latter will be of different material to the conductor and if the stress intensities in the materials of the joint are high when cold, they may be excessive when the

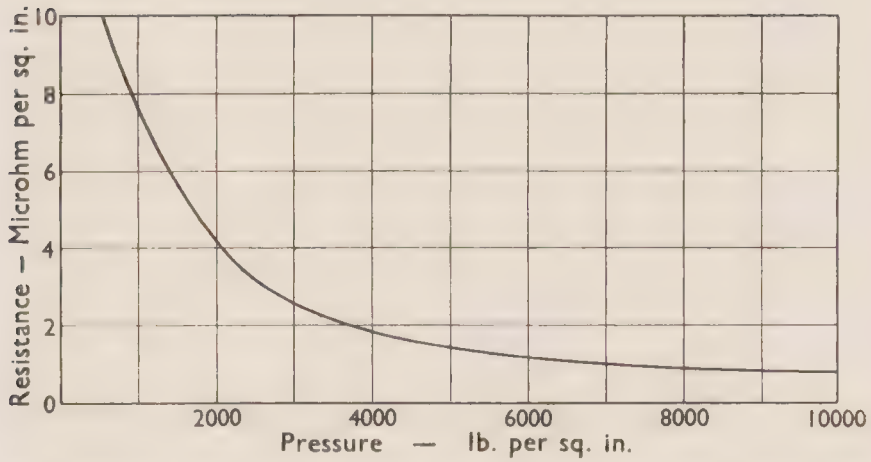


FIG. 17-6.—*Effect of Pressure on the contact resistance of a joint between two copper conductors (The Copper Development Association).*

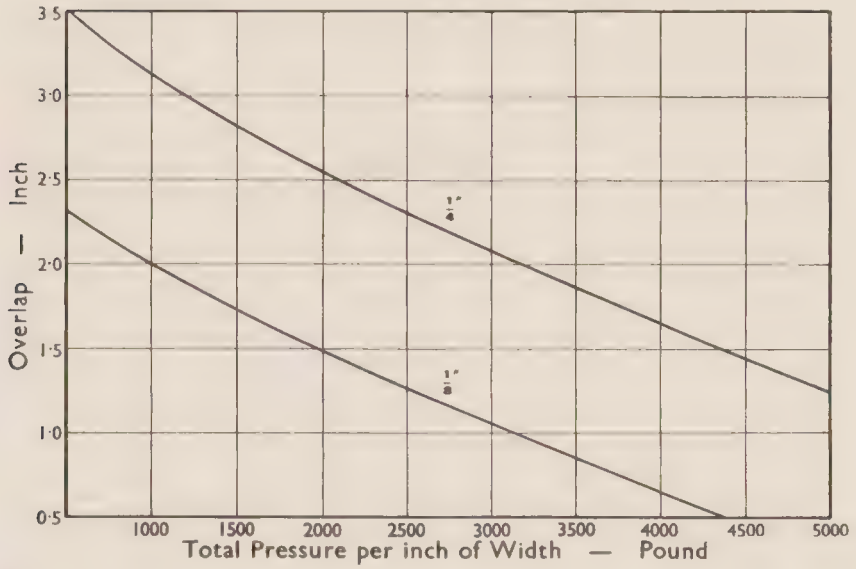


FIG. 17-7.—*Total Pressures required per inch of width for joints to give 100% efficiency between flat copper strips (The Copper Development Association).*

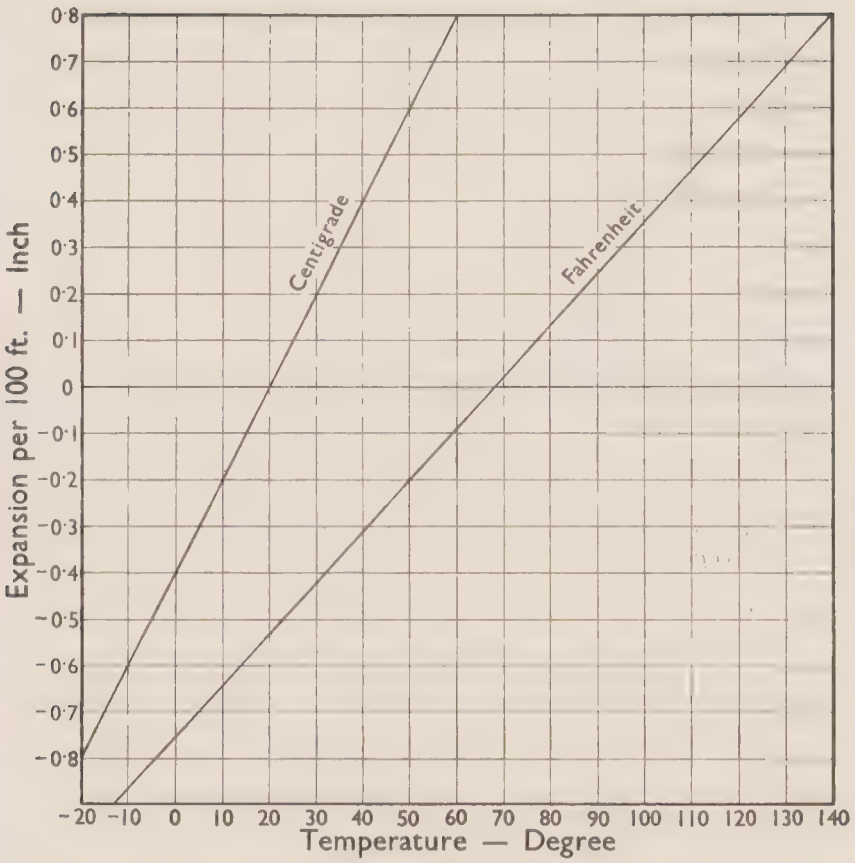


FIG. 17-8. *Thermal expansion and contraction of copper conductors relative to their length at 20°C. (68°F.) (The Copper Development Association).*

joint is warm so that a permanent set in one part may arise. It should be borne in mind too that the bolts will not be at the temperature of the conductor since they are not directly heated by the current. In the "Electrical Journal," Sept., 1933, Vol. 30, the following average loadings on steel bolts, tightened by an average workman with a standard spanner are given.

Bolt Diam. Inch	Force per bolt Pounds	Stress in bolt Pounds/sq. inch
¼	400	15,000
⅜	960	14,000
½	1,580	12,500
⅝	1,820	9,000
¾	2,560	8,500

The amount of overlap at joints is not dependent on the current transfer, because as previously indicated the whole of the area is not effective in this respect. Rather, the overlap is determined by the number of bolts necessary to obtain the required pressure and, what is important, to prevent the ingress of gases into the active area of the joint. Both copper and aluminium in contact with air rapidly oxidise. This leads to overheating at joints as it introduces a high resistance film. The provision of a good overlap helps to prevent this, particularly if coupled with the simple precaution of smearing the surfaces at the joint with vaseline, and scratch brushing just prior to making a joint. It is a good rule for copper to make the overlap equal to the width of bars being joined, and for aluminium, twice the width of the bars.

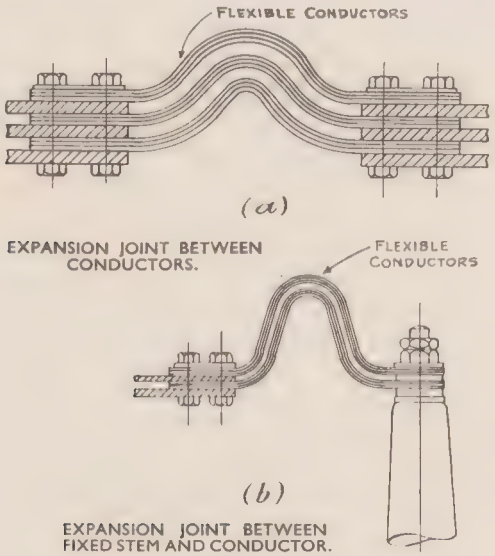


FIG. 17-9.—*Forms of expansion joints.*

Joints between copper and aluminium need special attention, as electrolytic action may arise between the metals in the presence of moisture. This can be avoided by introducing a bimetal connector, such as a sheet of tinfoil between the two conductors.

EXPANSION AND CONTRACTION.

Allowance must be made in all busbar or conductor arrangements of any considerable length for expansion and contraction which occurs with variation of temperature. Fig. 17-8 gives curves to determine the expansion or contraction of copper conductors relative to their length at 20°C. (68°F.). Thus the total change in length per 100 feet of a copper conductor between temperatures of 0°C. and 40°C. will be 0·4 + 0·4 = 0·8 inches. The expansion or contraction of a copper conductor relative to any temperature other than 20°C. can be ascertained by drawing the line of zero expansion through the point of intersection of the curves and the ordinates corresponding to the temperature required.

In considering the problem of expansion and contraction it must be remembered that the conductor has a substantially higher co-efficient of linear expansion than has the steel structure supporting the conductor, and further, the latter is at a much lower temperature than the conductor. In long runs, the introduction of flexible joints will take care of expansion and contraction, typical forms being shown in Fig. 17-9. In short runs, elongated holes at joints may be sufficient.

Forces on Busbars and Conductors under Short-Circuit.

The forces imposed on busbars and connections, and on their supports, during short-circuit may be very considerable.

Details have been given in Chapter XIII, immediately following the sections describing the methods of calculating fault currents.

BIBLIOGRAPHY.

"B.S. 159."

Copper for Busbars, The Copper Development Association, Publication No. 22.

"Temperature Rise of Busbars," H. B. Dwight, G. W. Andrew and H. W. Tileston, "General Electric Review," May, 1940.

Electric Switch and Control Gear, C. C. Garrard (Benn Brothers).
The Calculation and Design of Electrical Apparatus, W. Wilson (Chapman and Hall).

"The Current-Carrying Capacity of Solid, Hard Copper and Aluminium Conductors," Melsom and Booth, "Journal I.E.E.," Vol. 62, No. 335, November, 1924.

The Switchgear Handbook, Vol. 1, W. A. Coates and H. Pearce (Sir Isaac Pitman and Sons, Ltd.).

"Skin Effect in Tubular and Flat Conductors," H. B. Dwight, "Journal A.I.E.E.," 1918, page 977.

"The Rating of Copper Conductors," A. Bannister, "Metropolitan-Vickers Gazette," Sept., 1934.

Note.—The reader will find a wealth of information on heat generation, heat dissipation from surfaces, and heat conduction through dielectrics in *The Switchgear Handbook* referred to above.

CHAPTER XVIII

INSTRUMENT AND PROTECTIVE TRANSFORMERS

THE use of current and voltage transformers in switchgear equipments must be considered from two angles; that of accuracy from a metering view-point and that of short-circuit conditions from the switchgear view-point. While consideration may be given to these separately both are equally important and neither can be overlooked and at certain points they intersect, where one has to choose between a high fault ability and a poor accuracy or vice versa. Current transformers, in particular, while being an auxiliary piece of equipment essential for a specified purpose, are nevertheless just as much part of the complete switchgear equipment as any other and unless selected in relation to the equipment as a whole, may be a weak link. Being a series piece of apparatus, the current transformer is subject to all the forces of short-circuit of which more will be said later.

CURRENT TRANSFORMERS.

If a current transformer could be produced in which the primary and secondary ampere-turns were exactly equal, and in consequence the secondary current always directly proportional to the primary current, many of the difficulties of this piece of apparatus would disappear. Core material being imperfect, this ideal case cannot be achieved. This is because in order to induce the essential magnetic flux in the core (which in turn causes the secondary voltage) a number of ampere-turns are necessary and these upset the balance. We are left, therefore, with the condition that the secondary ampere-turns are equal to the primary ampere turns plus the exciting ampere-turns. This is illustrated in Fig. 18-1 where the symbols represent :

E_P	=	Primary voltage.
E_S	=	Secondary voltage.
$\varnothing$	=	Flux.
I_L	=	Primary Current Iron Loss Component.
I_M	=	Primary Current Magnetising Component.
I_E	=	Total Exciting Current.
I_S	=	Secondary Current due to connected burden (inductive)
I_S^1	=	Equivalent Current (Is) in primary.
I_P	=	Total Primary Line Current.

In Fig. 18-1 unity ratio is assumed and the general theory of the transformer is that in order to supply the losses which occur in any core of magnetic material, current must be present (I_L) in phase with the primary voltage, while in order to magnetise the core, another current, at right angles to the primary voltage, must be supplied (I_M). Thus, to excite the transformer we have two currents which, when combined vectorially, give the total exciting current (I_E). When a burden is connected to the secondary of the transformer a current (Is) is produced which lags behind the voltage and corresponds to the reversed current (Is) in the primary.

Combining (Is) and (IE) vectorially, we obtain the total primary current (IP), greater in magnitude than (Is). If each of the factors related above varied in the same proportion, curves drawn to show the ratio and phase angle errors against percentage rated primary current would be straight lines. Exciting current remains the offending factor, and the exciting ampere-turns for a given impedance in the secondary circuit are a larger proportion of the total at lower values of primary current. Secondary current will reduce in the same proportion as the primary current, and the secondary impedance being fixed, the secondary voltage and flux density follow suit. As the permeability of the iron does not vary proportionally to the flux density, the exciting current (IE) follows a non-linear law. The result is that both the ratio and phase angle curves take an upward bend at lower values of primary current, as shown in Fig. 18-2. Because of these basic

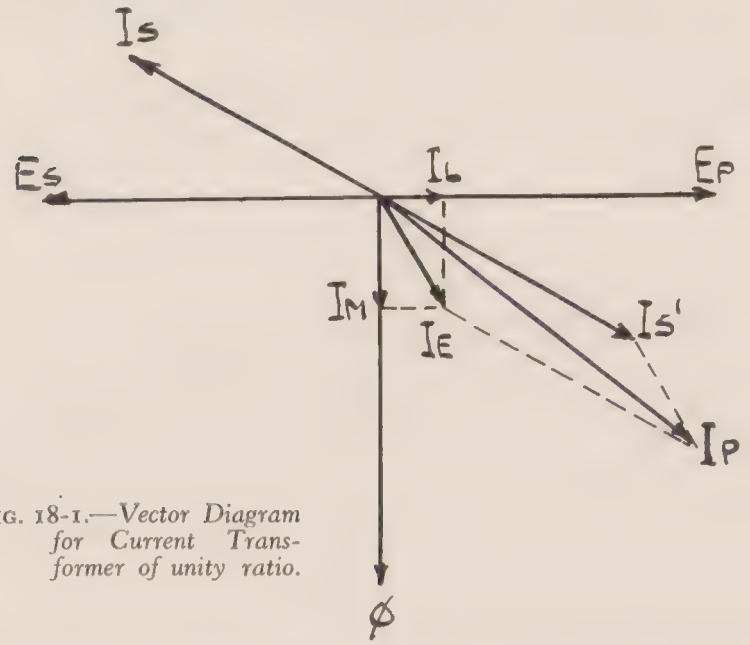


FIG. 18-1.—*Vector Diagram for Current Transformer of unity ratio.*

facts, it will be apparent that for metering transformers where accuracy is of vital importance it is essential that a ratio should be chosen with the primary as near as possible to the full load current.

Improvement in current transformer performance can be obtained only by a reduction in exciting ampere-turns, and this may be achieved in three ways :—

(*a*) By the use of improved magnetic material with low losses and high permeability.

(*b*) A reduction in the perimeter of the core material.

(*c*) Lower magnetic flux density.

The measure of improvement which can be obtained is often no more than a compromise, and experience becomes a deciding factor. Should the burden imposed by the secondary leads become considerable with the more

usual secondary current of five amperes (this is often the case in outdoor installations having long secondary leads between the outdoor transformers and the connected load in a remote control room) it is advantageous to adopt a 1 or 0·5 ampere secondary current. Since the burden is expressed as I^2R, these reductions in secondary current mean a considerable reduction in the burden. On the other hand, it involves an increased number of secondary turns, but this in turn enables a closer correction of turns ratio to compensate for the reduction in secondary current due to core-loss and magnetising ampere-turns.

The highest accuracy in a current transformer is obtained when :—

(1) The core material is of the highest grade.

(2) There are a large number of ampere-turns.

(3) The connected burden is small.

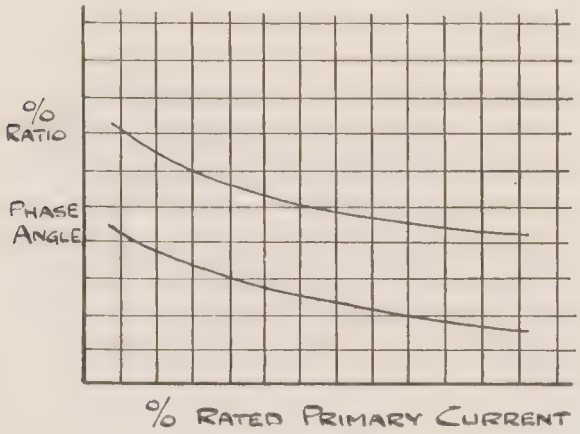


FIG. 18-2.—*Typical ratio and phase angle curves.*

The use of ordinary transformer iron is general where accuracy is not important ; an improvement is achieved by the use of a composite core, *i.e.*, a core of ordinary silicon iron with a packet of high permeability alloy, *e.g.*, mumetal, while the highest possible accuracy is obtained with cores made up completely of mumetal.

For other reasons (short-circuit) the bar primary or bushing type transformer is most suitable for use with modern switchgear of high breaking capacity, but there is a limitation here in that we have only one primary turn. With ordinary cores, this means one can rarely use this type on circuits of low primary current. The introduction of mumetal allows the type to be used for lower primary currents, especially if the secondary current is 1 or 0·5 amperes.

Connected burdens should be kept as low as possible, and as indicated earlier, the accuracy should be specified at or near to the actual burden, *e.g.*, if the connected load is 4 VA, and class CM accuracy is required, it is uneconomical to call for this accuracy at 15 VA as is so often done. The correct way is to call for 5 VA transformers. In a metering equipment it

is desirable to use separate current transformers for the purpose, using other transformers for apparatus not requiring high accuracy, *e.g.*, overload coils.

The following table gives an indication of the performance of current transformers having different core materials.

Primary Amps.	Silicon Iron Core (100% Si Fe)		Composite Core of Si Fe + Ni Fe (up to 50% Ni Fe)		Composite Core of Si Fe + Ni Fe (up to 75% Ni Fe)		Nickel Iron Core (100% Ni Fe)	
	VA	Class	VA	Class	VA	Class	VA	Class
50	—	—	4 2	D C	2	CM	5	CM
100	15	D	5	C	5	CM or B	3	BM
150	15	D	10	C	15 5	CM B	5	BM
200	15	D	15	CM	15	B	10	BM
300	30	D	15	CM	15	BM	—	—
400	50 15	D C	15	BM	—	—	—	—
600	50 20	D C	15	BM	—	—	—	—
800	30 5	C BM	20	BM	—	—	—	—
1000	30 5	CM BM	15	AM	—	—	—	—
1500	15 30	BM CM	15	AM	—	—	—	—

Note.—At 100 primary amp. and below, 1 amp. secondary windings are recommended.

In determining the burden connected to any current transformer a true value can only be obtained by deriving the total impedance vectorially instead of arithmetically. The latter is usually higher than the former, particularly where apparatus of low power factor is connected. The true impedance is Z3 in Fig. 18-3 and not Z1 + Z2, and I^2Z3 is the true burden.

Emphasis has been laid on the need to specify outputs as near as possible to the actual connected burden. On the other hand, it is equally uneconomical to specify undue accuracy. For example, for the operation

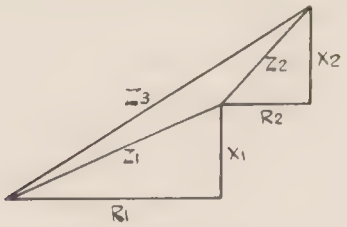
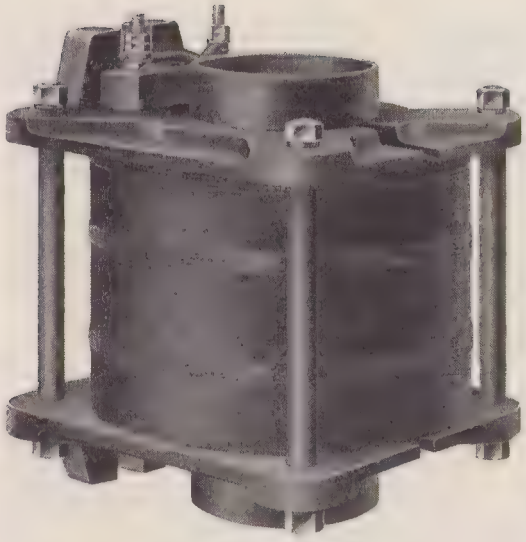
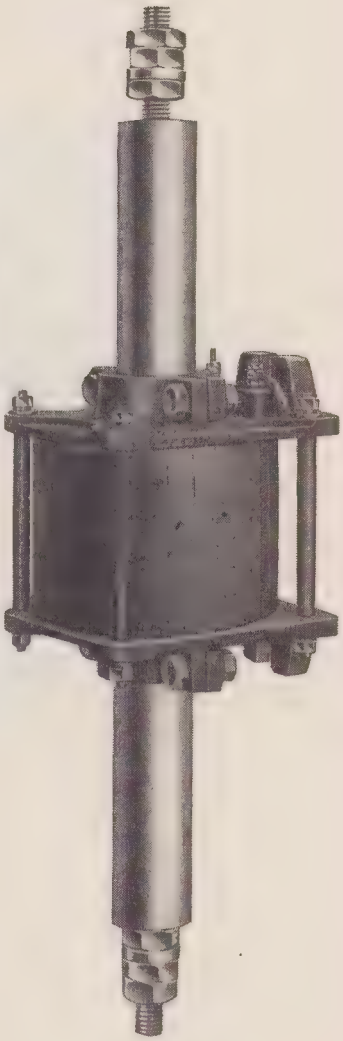


FIG. 18-3.



(*a*)



(*b*)

FIG. 18-4.

Typical Bar Primary Current Transformers.

(*a*) *Without primary conductor.*

(*b*) *With primary conductor and bushing.*

of ordinary overload coils it is unnecessary to specify anything more than Class D. The following table is given as a guide to suitable accuracies.

Application.	Class
Precision Industrial Metering	AM
Industrial Metering, sub-standard grade to B.S. 37	BM
Industrial Metering, commercial grade to B.S. 37	CM
Substandard Indicating Wattmeters	A
First Grade Indicating and Graphic Wattmeters	B
First Grade Indicating and Graphic Ammeters	C
For purposes where ratio is of less importance than in the above, *e.g.*, ammeters where approx. values only are required. Also overload trip coils	D

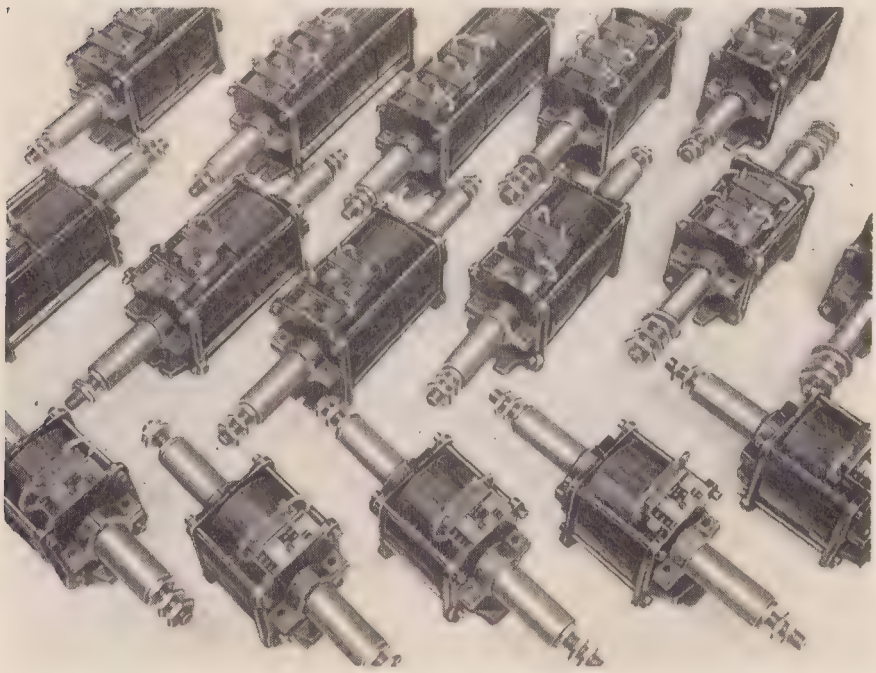


FIG. 18-5.—*Bushing Type Current Transformers.*

Figs. 18-4 and 18-5 illustrate representative examples of bar primary and bushing type current transformers, Fig. 18-5 including bushing types with one, two and three secondary windings. Fig. 18-6 illustrates two types of compound filled wound type transformers, one with primary terminals at opposite ends, the other with the terminals at the same end.

Current transformers for protective gear tend, with modern forms of such gear, to be of a standard type rather than a type specially built and matched for the purpose. Nevertheless, the conditions to be met differ

from those applying to metering and measuring instrument current transformers, and the latter are not necessarily suitable for protective purposes. The metering current transformer must maintain a specified accuracy from a small fraction of its rated primary current up to something approaching 50% overload. A protective current transformer on the other hand, must give a predetermined performance from its rated primary current up to a maximum value of through fault current which may be 20 times the normal primary current. At these heavy currents, the core may be saturated and in those forms of protective gear where a straight line characteristic is essential, the core is built with distributed air gaps, thus avoiding saturation over the working range. Where this method is not used, *i.e.*, with a solid core, care must be taken to see that saturation does not occur and that the secondary current remains a fixed percentage of the primary current. Any such change in ratio may cause sufficient current to flow in the relay circuit

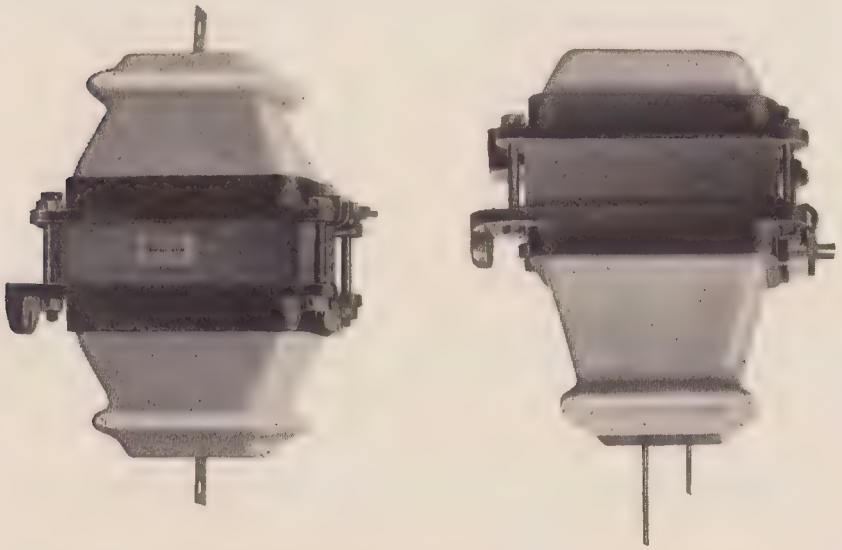


FIG. 18-6.—*Compound filled Wound type Current Transformers.*

to cause operation when a balanced form of protection is used. The chief cause of current transformer inaccuracy has been shown to be the magnetising current drawn from the primary side to produce flux in the core. If, in a balanced system of protection, there is any difference in the magnetising currents of the two transformers on any one phase, a " spill " current may flow in the relay circuit, and if of sufficient magnitude, will cause inadvertent operation of the relay. For this reason, it is often necessary to ensure suitable balance of transformers on test, pairing them for use in predetermined positions in the switchgear. When protective gear of the distance or impedance type is used, the need for accuracy at high overcurrent values is especially important. It is a need which must be carefully watched when current transformers of different types are used, such as wound primary and bar primary opposing each other.

SHORT-CIRCUIT RATING OF CURRENT TRANSFORMERS.

The situation can easily arise where current transformers can constitute the weakest link in an electrical circuit, unless they are selected having full regard to the short-circuit value of the circuit. Being a series connected piece of apparatus, the primary winding must be capable of withstanding the stresses due to the through short-circuit current for such periods of time as the protective gear and the inherent tripping time of the circuit-breaker determines. The more turns there are forming the primary winding the greater the effect of the short-circuit on that winding. For this reason, it will be clear that the single turn type (bar primary or bushing, Figs. 18-4 and 18-5) will be best from the point of view of short-circuit ability.

Two factors concern this feature in current transformers, viz. :—

Thermal Limit.

Mechanical Limit.

The first of these depends on a value of maximum permissible density in the primary winding for a given time. The following table is taken from B.S. 81.

Rated Time in seconds	Current Density in Amperes per sq. inch .
0·5	150,000
1·0	106,500
2·0	75,000
5·0	48,000
10·0	33,000

Using these values, and assuming that it is required to ascertain the minimum section of primary conductor for a current transformer to be used on a system where the short-circuit value is 150 MVA at 11 kV, we get

$$\text{R.M.S. S.C. Current} = \frac{150 \times 1{,}000}{11 \times 1{\cdot}73} = 7{,}900 \text{ amperes.}$$

On the basis of the short-circuit being cleared in 0·5 seconds, the cross sectional area will be,

$$\frac{7{,}900}{150{,}000} = 0.053 \text{ sq. in.}$$

The values of current density given in the foregoing table are such as to ensure a temperature rise not exceeding 200°C. in any part of the transformer.

The mechanical limit depends on the peak value of short-circuit current (2·55 times the R.M.S. value in the first half-cycle), the number of turns in the primary winding, and the design of the coil structure. The electromagnetic forces in the primary winding (tending to burst a multi-turn winding) are proportional to the square of the ampere-turns and it follows that the lower this value, the better the transformer will be able to withstand short-circuits. For multi-turn transformers an "overcurrent factor" is generally given. For commercial grades of ordinary design, overcurrent factors range from 50 to 100 based on a time of 0·5 seconds. Designs are available having overcurrent factors from 200 to 400 on the same time basis. Above this, multi-turn transformers are impracticable and the bar primary or bushing type must be used.

The lower the specified accuracy and output, the stronger can the transformer be built and the higher its overcurrent factor, and this emphasises again the undesirability of over-specifying these requirements. It is important, when inviting offers for current transformers alone, to give an indication of the short-circuit conditions with which they will be associated.

The short-circuit rating of any range of current transformer can be checked on a test plant, as used for circuit-breaker testing. It is, however, not possible to make this check on every transformer for obvious economic reasons and after a type test, subsequent individual transformers are checked for similarity of construction, core cross-sectional area, ampere-turns and insulation. A synthetic test for short-circuit rating can be carried out on a basis of primary winding resistance. The relation of overcurrent factor to primary resistance is shown in Fig. 18-7.

If, in a given design of current transformer, the overcurrent factor is 100, and taking a range up to 400/5 amperes, we can obatin a curve similar to that in Fig. 18-8 which shows the relation of ratio to primary resistance. For each ratio there is a maximum permissible r.m.s. short-circuit current to which the transformer may be subjected, *i.e.*, equal to the primary current multiplied by the overcurrent factor. Taking, for example, a given r.m.s. short-circuit current of 20,000 amperes, and a current transformer ratio of 400/5 with an overcurrent factor of 100, it is clear from Fig. 18-8 that this transformer is quite suitable for the duty. For this short-circuit current a 200/5 ratio represents the minimum with an overcurrent factor of 100, or expressed another way, the resistance of the primary of this 200/5 current transformer is the *maximum* which is permissible for a system short-circuit of 20,000 amperes. If lower ratios are required, then the resistance must not be higher than that corresponding to point X but must follow the horizontal line XY for all lower ratios, subject to similarity in construction. This leads to the conclusion that in a given range of current transformers, once the overcurrent factor becomes the limiting feature for a given short-circuit current, any transformer of ratio lower than that corresponding to the point X must not have a primary resistance higher than the critical value represented by point X. Certain variations in resistance for given conditions occur between transformers of different construction, but for a given line of transformers all of the same construction, comparative measurements of primary resistance constitute a test which can be carried out on a production basis and closely check the value of short-circuit rating.

Voltage Transformers.

The voltage transformer is a shunt-connected piece of apparatus and as such has not undergone the change which has occurred in current transformer design.

In general, the voltage transformer works in a manner similar to a power transformer, an external load producing a current in the secondary. Due to internal losses, the ratio will differ from the ratio of primary to secondary turns, and there will be a phase difference between primary and secondary voltages.

These errors (ratio and phase-angle) are functions of the secondary current and therefore if the secondary load is fixed, meters or instruments can be calibrated to allow for the errors.

Standardisation has determined that the secondary voltage shall be 110 volts between lines, thus permitting the windings of instruments and meters to be wound for this standard voltage. Connection to the lines is

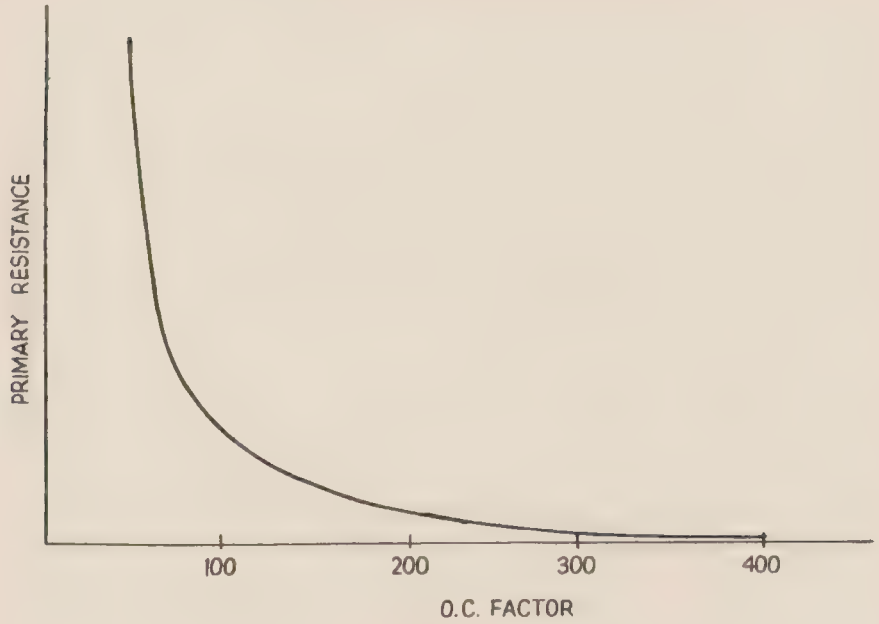


FIG. 18-7.

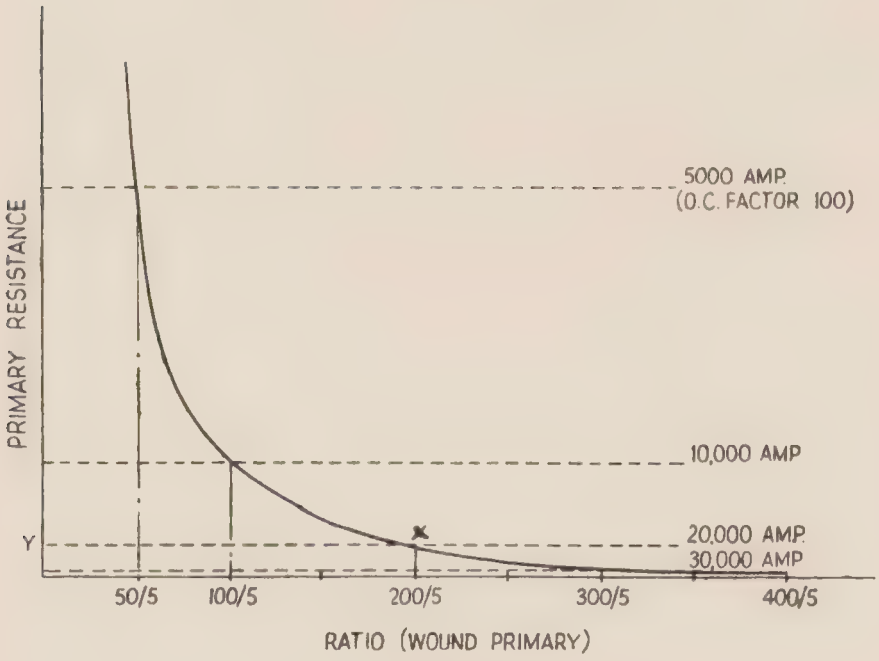


FIG. 18-8.

invariably through fuses in order to disconnect the transformer from the supply in case of breakdown.

With the secondary short-circuited, the high short-circuit impedance limits the current in the primary to a very small value and insufficient for satisfactory fuse operation, except for very fine fuse wires. These, if used, would be very fragile and subject to the effects of corona. The fuses used, therefore, can only be regarded as *protecting the system* against a transformer breakdown and *not to protect the transformer* itself. Secondary fuses are necessary to protect the transformer against faults in the secondary wiring or connected apparatus. These fuses must be located as close to the transformer as possible so that lengths of unprotected wiring are avoided. Secondary fuses are usually rated well above the secondary current so that the resistance introduced is low enough to have no effect on voltage at the instruments. For a 50 VA output, secondary fuses of 2 ampere rating and for 100 VA, 4 ampere, are usual.

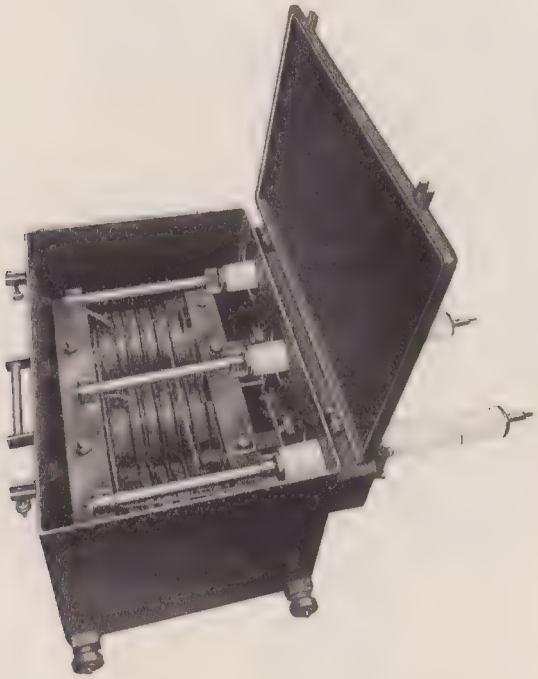


FIG. 18-9.—*Plug-in type Voltage Transformer.*

Primary fuses of the high resistance type are now standard for system voltages up to and including 11 kV. A variety of types manufactured by the English Electric Co., are available for use in air or in oil. Above 11 kV the use of separate limiting resistances in series with the fuse is general.

Means should be provided to isolate voltage transformers either by a separate *gang* operated isolating switch or by a switch built in. The latter form is usually adopted where the voltage transformer is of the plug-in type as shown in Fig. 18-9. In this type the primary contacts are spring

loaded making point pressure contact with the fixed block terminals. In another type a snap action lever switch must be operated before withdrawing the transformer.

For voltages up to and including 3·3 kV, air insulated or compound filled transformers are an economical form, especially for use in metalclad

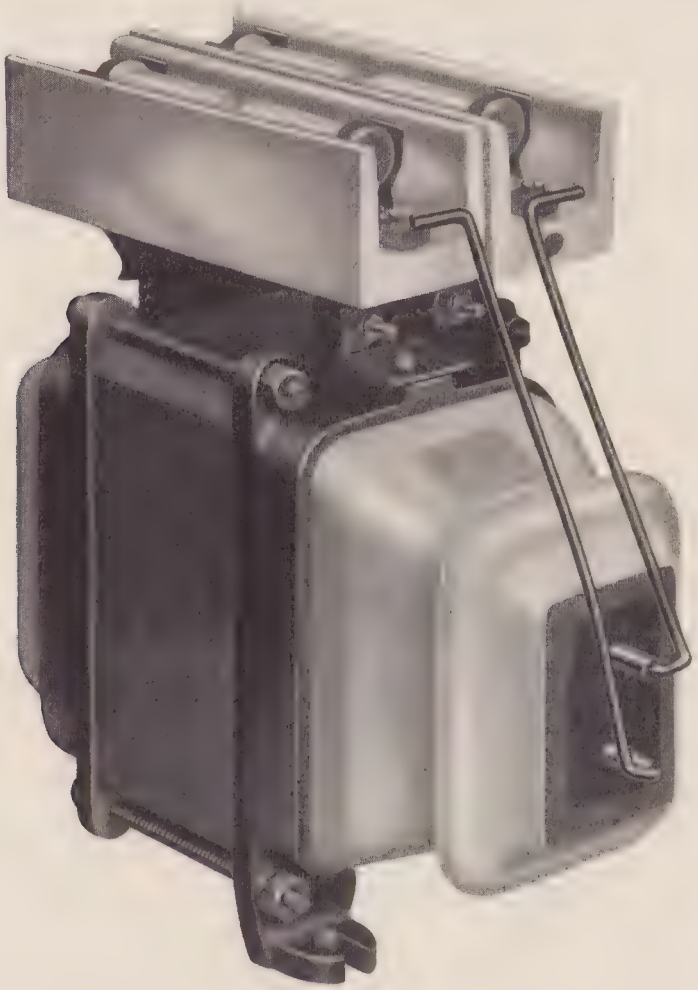


FIG. 18-10.—*Compound filled type Potential Transformer up to 3·3 kV.*

gear. A typical compound filled type is shown in Fig. 18-10. For higher voltages, oil immersed units are usually employed.

Voltage transformers are essential in certain forms of protective gear, *e.g.*, directional, impedance. Where phase overcurrent fault relays only are used, the normal three-phase star/star transformer or two single-phase transformers connected in open delta is usually satisfactory as the secondary voltages between phases sufficiently represent the primary voltages under

fault conditions. For directional earth fault protection, however, it is necessary to provide connections which correctly reproduce the fault condition and give a voltage in phase with and proportional to the displacement of the transformer neutral from its normal condition. For this purpose it is necessary to earth the high-voltage neutral. The usual form of connection is shown in Figs. 18-11 and 18-12. From the former it will be noted that under normal conditions the vectors of secondary voltages form a closed triangle and no voltage appears across the open-delta secondary. From Fig. 18-12, it is seen than an earth fault on one line of the primary system converts this to a four-wire system, and the voltage

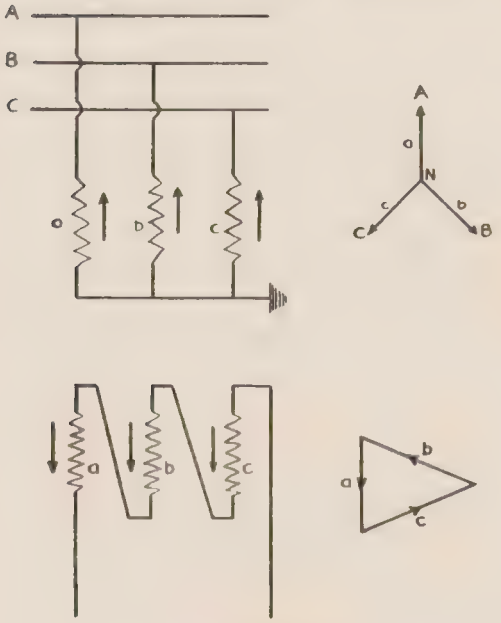


Fig. 18-11.

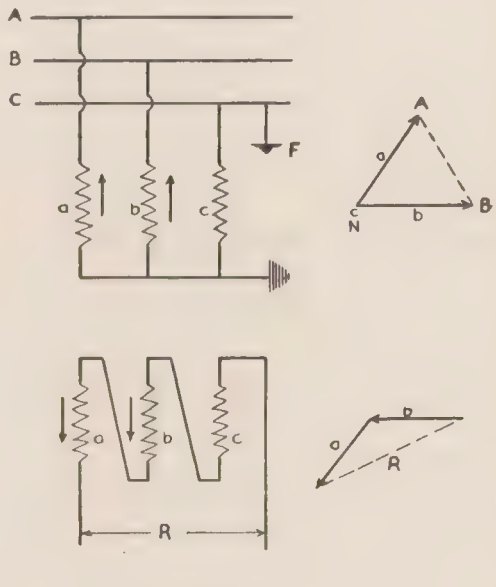


Fig. 18-12.

vectors, being proportional to the line currents, will be as indicated, leaving a voltage across the open-delta secondary. The value and phase of this residual voltage (R) will depend on the magnitude of the earth fault current and the impedance of the fault path. When a dead earth fault occurs on one line adjacent to the voltage transformer, the residual voltage, which is the voltage impressed on the relay, can be as high as three times normal, *i.e.*, 330 volts. This will be clear from Fig. 18-12 where it is noted that the primary voltages are 60 degrees apart and the secondary voltages are 120 degrees apart. R will therefore be three times normal for the reason that the primary voltages are root-three times normal giving root-three times normal voltage across the open-delta and a further root-three times due to the 120 degrees displacement of secondary voltages.

Fig. 18-12 also indicates that an earth fault on one primary line short-circuits the transformer winding connected to that line. In the normal transformer with a three limb core the resultant flux due to the two healthy lines returns through the limb of the faulty line inducing a heavy short-

circuit current in the winding on that limb. A voltage is induced in the winding on that limb. A voltage is induced in the corresponding secondary winding and the voltage across the open point of the delta will not be the true residual. In order to obviate this it becomes necessary to provide a low reluctance return path of sufficient cross section to carry the maximum value of unbalanced flux without saturation. This is provided by the five limb core as shown in Fig. 18-13. This arrangement increases the size of the transformer and may cause inconvenience in mounting in fixed frame

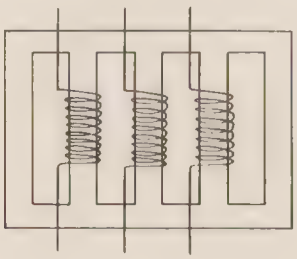


FIG. 18-13.—*Elementary Diagram of Five Limb Transformer.*

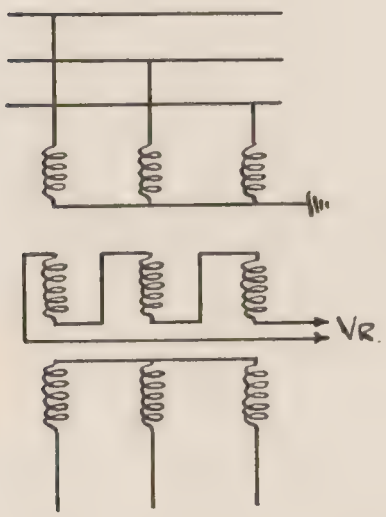


FIG. 18-14.—*Tertiary Winding on Voltage Transformer to give residual voltage (Five Limb Transformer).*

sizes of switchgear. An alternative is the use of three single-phase transformers, but space is an all-important factor.

If it is essential to use the voltage transformer for other purposes, *e.g.*, instruments or meters, for which the normal star/star connection is essential, the needs of the protective gear can be satisfied from a tertiary winding connected in open-delta to give the residual voltage. The connections for this are shown in Fig. 18-14.

The importance of correct voltage representation in directional forms of protective gear makes it essential that the switchgear manufacturer shall be given full details of the protective gear if this is to be purchased separately.

BIBLIOGRAPHY.

" INSTRUMENT TRANSFORMERS," J. G. Wellings, " B.T.H. Activities," May, 1936.

Instrument Transformers, B. Hague (Pitman and Sons, Ltd.).

" INSTRUMENT TRANSFORMERS," J. G. Wellings and C. G. Mayo, " Journal I.E.E.," Vol. 68, 1930.

Relay Systems—Theory and Application, Monseth and Robinson (McGraw Hill Publishing Co.).

" British Standard Specification No. 81."

Automatic Protection of A.C. Circuits, G. W. Stubbings (Chapman and Hall).

Protective Gear Handbook, M. Kaufman (Pitman and Sons).

" INSTRUMENT TRANSFORMERS," A. Hobson, " Journal I.E.E.," Vol. 91, Part II, No. 20, April, 1944.

CHAPTER XIX

SWITCHBOARD INSTRUMENTS

In the present chapter it is not proposed to consider the problems of metering, which form a subject apart involving consideration of the requirements of the purchaser and a knowledge of his method of charging or segregation of process costs and the like.

Instead, only those *indicating* instruments generally common in switchgear use are considered, it being further noted that even so, no attempt is made to consider the detail design of such instruments.

The improvement in the design and performance of switchboard instruments has kept pace with the general improvement in the design of switchgear. Once satisfactorily installed, modern instruments seldom give trouble, but damage is frequently caused by rough handling during transit or erection. Manufacturers do their best to prevent damage by careful packing, and users should not lose sight of the fact that all instruments are comparatively fragile and need careful treatment.

The accuracy of switchboard instruments is dealt with in British Standard Specifications, Nos. 37 and 89.

Indicating instruments should have clear, openly divided scales of reasonable length. Long scales are easy to read, but do not necessarily enable more accurate readings to be taken. An 8-inch scale may have 50 divisions and a 16-inch scale 100 divisions, but the error of the instrument may be equal to one division of the 8-inch scale and two divisions of the 16-inch scale. The scale of switchboard instruments should not be crowded with too many divisions; a mark for every two per cent. of the full scale reading is usually quite sufficient.

With fluctuating loads a well-damped movement is essential. Moving coil instruments are naturally well damped, and other types are fitted with damping chambers or eddy current dampers. The aluminium vane has to be a close fit in the damping chamber and rough handling of an instrument may cause the vane to foul the wall of the chamber and thus cause sticking.

Indicating instruments for switchboard mounting are usually of the round pattern, but edgewise instruments, either vertical or horizontal, may be used if preferred, or to make better use of the space available on the board. Edgewise instruments are not easy to read unless the observer stands immediately opposite the scale, and may look somewhat unsightly unless mounted with the scales flush with the panel, a method of mounting which necessitates large holes in the panel.

Busbar and synchronising voltmeters and summation ammeters are usually of the sector pattern with illuminated dials. Some edgewise instruments can be fitted with lamps, but the lamp should be mounted outside the case.

Busbar voltmeters may have a portion of the scale suppressed to give clear readings over the working range. Troubles may be encountered if it is desired to suppress more than about 50 per cent. of the full scale reading.

The scales of ammeters and indicating watt-meters should be chosen so that the maximum overload which can be carried by the circuit for an appreciable length of time may be read. About 25 per cent. overload is a useful margin, but more may be required on traction or other widely varying loads.

Voltmeters should have the normal voltage reading a little past the middle of the scale, and on moving iron instruments the lower readings may be cramped, as shown in the illustration of a sector pattern voltmeter.

Indicating instruments which have a definite zero mark should have a zero adjusting device accessible from the exterior of the case. Pointer clamping arrangements are necessary for instruments with heavy moving systems to avoid damage in transit.

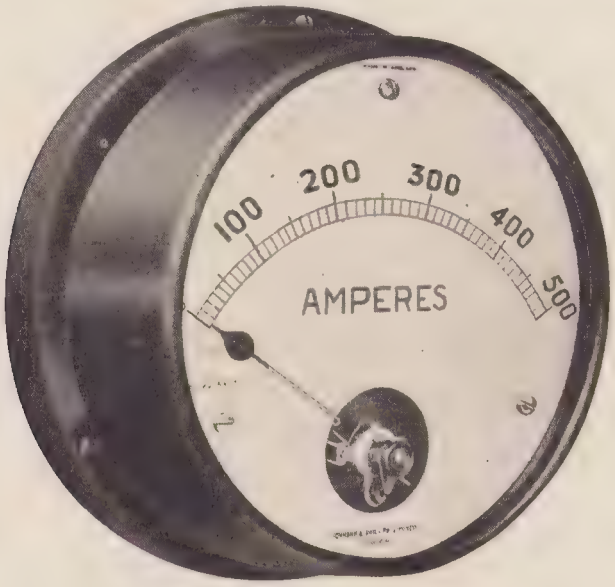


FIG. 19-1.—*Moving Coil Ammeter.*

MOVING COIL INSTRUMENTS.

Permanent magnet moving coil instruments are suitable for use on d.c. circuits only, and ammeters are operated from shunts, which may be contained in the instrument case for currents up to about 50 amps.

The scale of moving coil instruments is evenly divided, and the zero mark can be central or displaced so that reverse current or voltage can be read.

Shunt leads are adjusted to a definite resistance, and the section of lead required may be considerable if a long run of lead is necessary; in some cases, when the current to be measured is not very great, it may be cheaper to take the main current cables to the switchboard rather than to provide long shunt leads. If large machines are situated some distance from the switchboard, the main field current may be read by connecting a voltmeter across the field terminals, the meter being mounted on the switchboard and calibrated in amperes on site against the readings of an ammeter temporarily connected in circuit.

MOVING IRON INSTRUMENTS.

Moving iron electro-magnetic instruments may be used on a.c. or d.c. circuits and are not seriously affected by the variations in frequency met with in commercial use. Ammeters may be direct connected in circuit for currents up to a maximum of about 800 amps. according to the size of the instrument case, but for a.c. work are usually operated from the secondaries of current transformers. Moving iron instruments are not suitable for operation from shunts on a.c. circuits.

FIG. 19-2.—*Moving Iron Ammeter.*

The scale of moving iron instruments is not evenly divided, but in good designs is sufficiently open over the working range. The possibility of cramping portions of the scale is often valuable, so that an indication of current or voltage considerably above or below the normal working figure may be obtained with open divisions over the rest of the scale.

Ordinary moving iron instruments cannot be provided with a displaced zero, but a special form of central zero voltmeter is obtainable which indicates the difference of two potentials and may be used for paralleling.

INDUCTION INSTRUMENTS.

Induction ammeters and voltmeters were formerly used on a.c. circuits when a long scale was required, but with the advent of long scale moving iron instruments, the more expensive induction pattern has fallen into disuse to some extent.

For all ordinary conditions it is usually satisfactory to employ balanced load watt-meters and power factor meters, since great accuracy is seldom

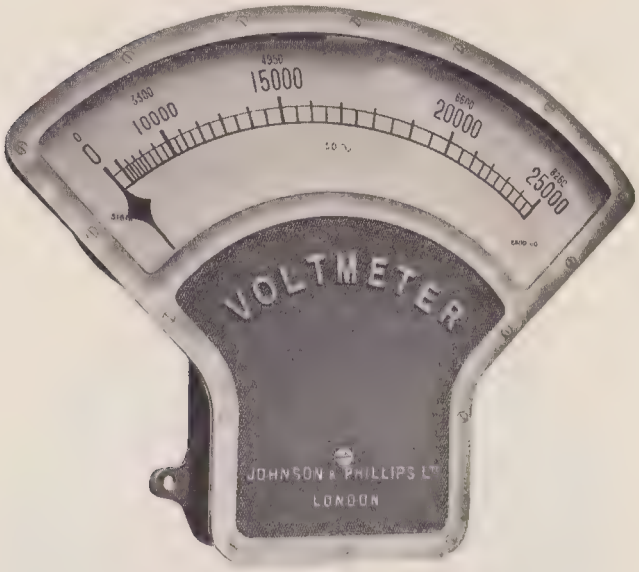


FIG. 19-3. *Sector type Moving Iron Voltmeter.*

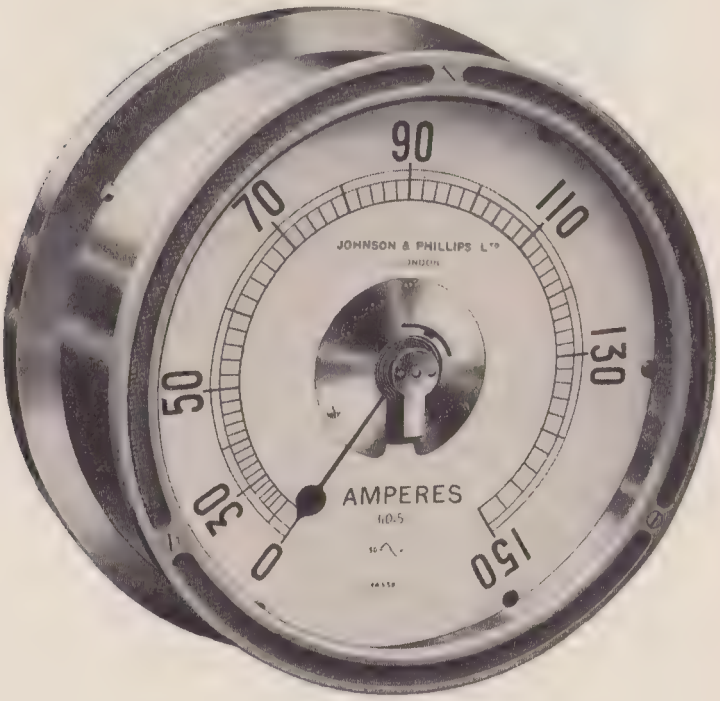


FIG. 19-4.—*Induction type Ammeter.*

required, but the more expensive unbalanced load type may be used on polyphase circuits where the amount of out of balance is considerable.

Both indicating watt-meters and power factor meters are somewhat expensive, and should not be specified unless they will be really useful; a power factor meter may be regarded as essential on alternator and converter panels.

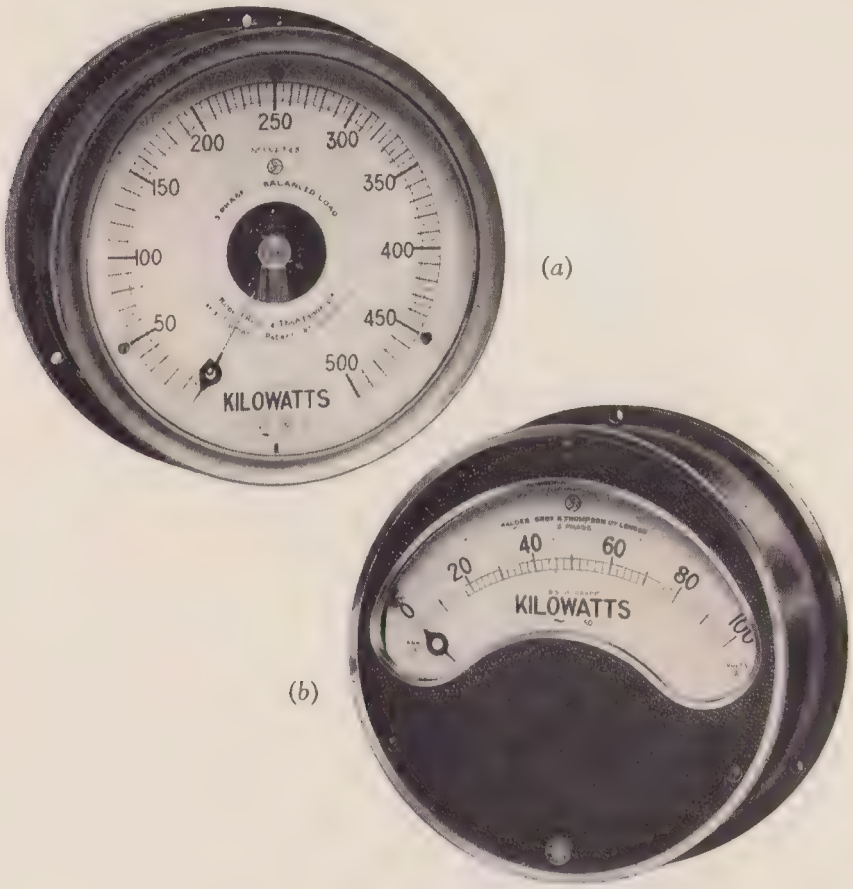


FIG. 19-5.—*Indicating Watt-meters.*
(*a*) *Induction Type.*
(*b*) *Dynamometer Type.*
(*Nalder Bros. & Thompson, Ltd.*).

Power factor meters, when first installed, are often found to read on the wrong half of the scale, or to indicate lead instead of lag, owing to incorrect phase rotation, and methods for correcting connections and checking accuracy are given later in this chapter. Power factor meters will not give correct indications on a small percentage of normal load.

Both indicating watt-meters and power factor meters are arranged for current transformer operation, but the voltage coils may be direct connected to circuits not exceeding about 600 volts.

SYNCHROSCOPES.

Lamps may be used for synchronising, but on any but the smallest installation it is advisable to provide a synchroscope which indicates the phase displacement between the busbars and the machine with considerable accuracy, and also shows whether the machine is fast or slow in speed.

Synchroscopes are usually provided with a lamp which is connected so as to glow or remain dark at the instant of synchronism. It is usually preferred to have the lamp bright at synchronism, as otherwise, should the filament break, a dangerous indication may be given. If synchronising

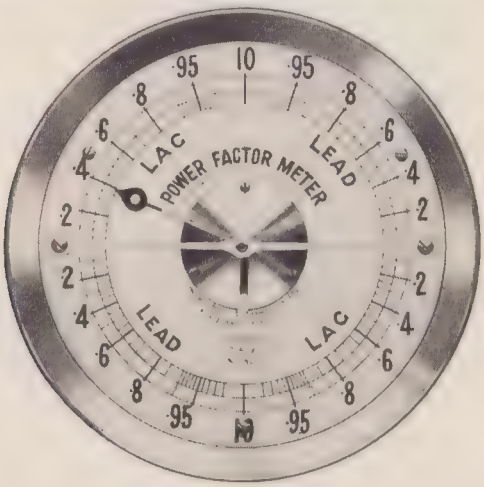


FIG. 19-6.—*Power Factor Meter*
(Nalder Bros. & Thompson, Ltd.).

is carried out without voltage transformers or between machine voltage transformers, it is necessary to add a small 1/1 ratio transformer to reverse the polarity of the two voltage circuits to give lamps bright at synchronism.

A synchroscope is available with a signalling attachment, consisting of two different coloured lamps, one of which lights when the incoming machine is slow, and the other when the machine is fast.

For small switchboards, an 8-inch dial synchroscope is large enough, but other sizes are available up to about 20-inch diameter.

FREQUENCY METERS.

There are two types of frequency meter, the resonance and the deflectional pattern.

The resonance pattern consists of a number of reeds tuned to vibrate at a definite frequency; an electro-magnet, energised from the circuit of which the frequency is to be measured, causes the reed, which has a natural period of vibration equal to the system frequency, to vibrate. Readings cannot be taken from any considerable distance, but instruments of this type are to a considerable extent independent of wave form, voltage, and temperature variation.

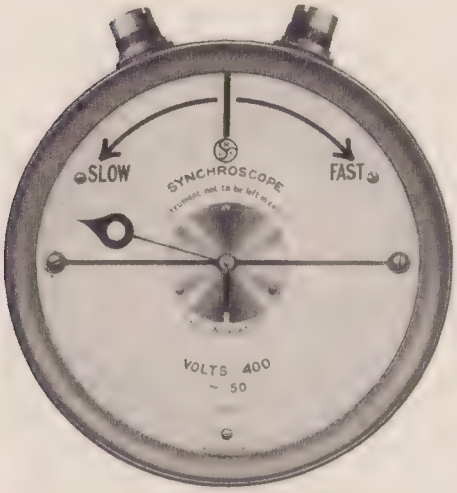


FIG. 19-7.—*Synchroscope with lamps (Nalder Bros. & Thompson, Ltd.).*

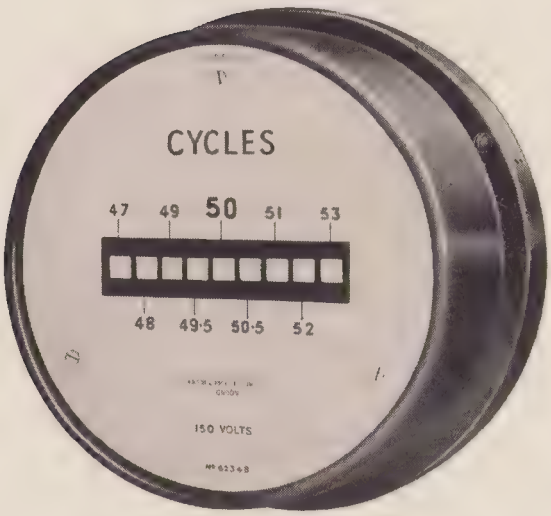


FIG. 19-8.—*Resonance (Vibrating Reed) type Frequency Meter.*

The deflectional pattern is provided with a pointer and scale, and readings can be easily taken. The instrument operates on the induction principle, a disc attached to the pointer taking up a position between the poles of two electro-magnets, the position varying with the frequency. Instruments of this design should not be affected by wave form and temperature variation, within wide limits.

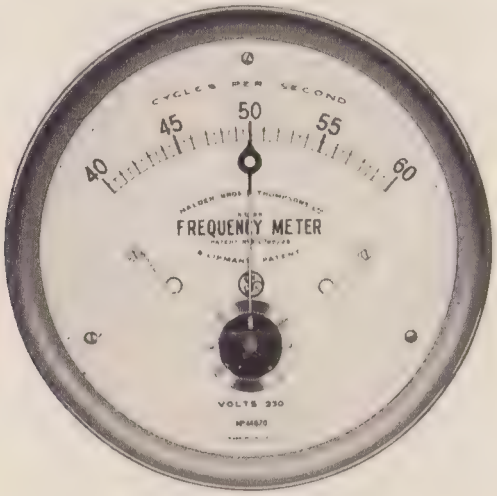


FIG. 19-9.—*Deflectional type Frequency Meter (Nalder Bros. & Thompson, Ltd.).*

RECORDING INSTRUMENTS.

Modern recording instruments may be obtained in various forms, the chief differences being in the inking arrangement and the form of chart.

The cheapest pattern employs a drum or disc chart which revolves once in twelve or twenty-four hours at a chart speed of about one inch or half inch per hour respectively. This pattern is quite satisfactory for attended situations and when high chart speeds are not required; but a form which is used to a greater extent employs a continuous chart long enough for a month's use at a chart speed of about one inch per hour.

Pen pattern recorders require refilling with ink every few hours on slowly varying records, and correspondingly oftener with widely varying loads, such as are met with on traction circuits. An inking system is available in which a comparatively large amount of ink is held in a reservoir and is siphoned over the pen point; this pattern is very useful for unattended substations.

"Inkless" recorders are made, the marking being obtained from an ink pad or a sheet of carbon underneath the chart. A steel ball or the like drops on to the chart at frequent and regular intervals at a point corresponding to the value of the current or voltage at the instant the marker drops; the record obtained is in the form of an almost continuous line. This system of marking is not suitable for rapidly or widely varying records.

The chart speed required is determined by the degree and rapidity of variation of the load or voltage to be measured and the damping of the

penarm. A speed of half or one inch per hour is usually sufficient for voltmeters, and one inch per hour for ammeters or watt-meters on reasonably steady mixed lighting and power loads. For traction, colliery, or other widely varying loads, a chart speed of three inches per hour or more may be necessary to give a clear record.

The pointer arm is usually provided with a dashpot, the degree of damping being increased if it is not desired to record instantaneous variations.

The usual form of recording frequency meter consists of a small synchronous motor driving a permanent magnet generator, the voltage generated being proportional to the speed of the motor and the frequency of the system; a recording voltmeter calibrated in frequency is operated from the generator.

FIG. 19-10.—*Recording Instrument (Amperes, Volts or Watts) (Nalder Bros. & Thompson, Ltd.).*

LEAKAGE INDICATORS.

DIRECT CURRENT.

For completely insulated systems a low reading ammeter is connected between either busbar and earth, and the leakage current read direct. The scale can be marked in ohms to give an approximate indication of the resistance of the main to earth. It is usual to provide a double range instrument to enable small faults to be detected.

For systems with the middle wire earthed, a centre zero ammeter is connected between the neutral and earth and indicates on either side of zero, according to whether the fault is on the positive or negative main The mid wire should be earthed through a resistance, the resistance being normally short-circuited by an overload circuit-breaker which opens on a heavy fault and inserts a resistance into the earthing circuit; the breaker can be provided with auxiliary contacts to light a lamp or ring a bell when it operates.

On 2-wire systems with one pole earthed, the leakage current from the insulated pole can be measured after load has been disconnected. The leakage ammeter should be double range and provided with a fuse to minimise the risk of burning out the winding should all load not be disconnected when the test is made.

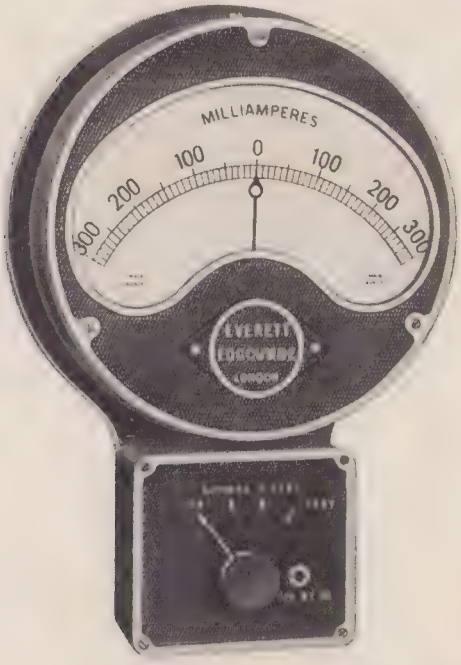


FIG. 19-11.—*Two Wire d.c. Leakage Indicator (Everett Edgcumbe & Co., Ltd.).*

ALTERNATING CURRENT.

For low-tension insulated systems a low reading ammeter with a selector switch may be provided. The instrument, with a resistance in series, is connected between each phase in turn and earth for testing the insulation of the phase. Normally the instrument is left connected to the three phases, so that it will indicate when a fault appears on any phase.

For high-tension insulated systems an electrostatic indicator may be used, connected between phase and earth. When the phase develops an earth fault the voltage across the indicator will be reduced and the instrument will give a reading approximately inversely proportional to the resistance of the fault. If preferred, an ordinary voltmeter may be used, operated from a potential transformer connected between phase and earth.

On systems with the neutral point earthed but not accessible, the cables supplying the circuit are passed through a special current transformer, the secondary of which supplies a leakage ammeter. Under ordinary conditions the vector sum of the currents in the cores of the cable will be zero, but an earth fault will unbalance the currents, and a secondary current will be induced in the transformer.

When the neutral point earthing connection is available, it is only necessary to put an ordinary current transformer in the earth connection and operate an ammeter from the transformer. The question of earthing the neutral point of a.c. system is dealt with in more detail in Chapter XXII.

Most forms of leakage indicator can be fitted with auxiliary contacts to light a lamp or ring a bell when a fault occurs.

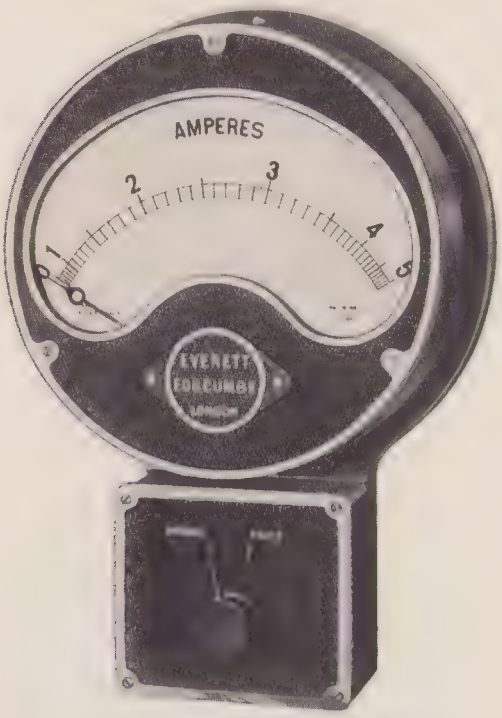


FIG. 19-12.—*L.T. a.c. Leakage Indicator (Everett Edgcumbe & Co., Ltd.).*

SYNCHROSCOPE CONNECTIONS.

When a new equipment is added to a switchboard, the new synchronising connections can be checked as follows:—

Open the feeder isolating switches or disconnect the cable connections to the machine or circuit. Close the busbar isolating switches and oil circuit breaker and plug in the panel as an incoming machine. The synchroscope should not indicate synchronism. With the synchroscope connected to the busbars only, the pointer should slowly rotate in a " slow " or clockwise direction.

PHASE SEQUENCE INDICATOR.

When connecting an instrument, such as a wattmeter or power factor meter, to a polyphase circuit, the order of phase sequence (or rotation) must be taken into account.

A useful instrument to determine the phase rotation is that known as the Phase Sequence Indicator, a typical model being illustrated in Fig. 19-13.

The instrument is essentially a miniature polyphase motor having a stator consisting of three coils and a metal disc rotor on which is marked an arrow. Spring grip terminals, with rubber shields, allow ready connection of the tails to the phase conductors, the terminals being coloured red, yellow and blue respectively.

After connection, the disc rotates and if the rotation is *with* the arrow, then the phase sequence is red, yellow, blue. If the rotation is *opposite* to the arrow, the phase sequence is reversed, that is, the voltages are reaching a maximum in the order red, blue, yellow. The interchange of any two leads will cause the disc to rotate in the direction of the arrow, and the correct phase sequence is thus determined.

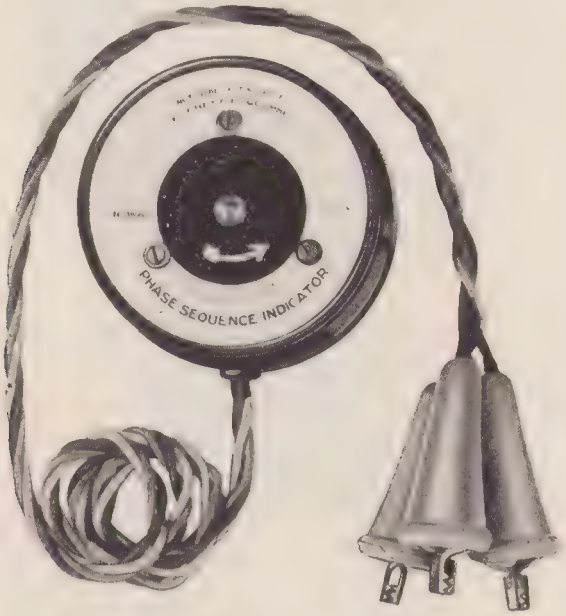


FIG. 19-13.—*Phase Sequence Indicator (Everett Edgcumbe & Co. Ltd.).*

MINIATURE INSTRUMENTS.

In Chapter XV it has been noted how neat the modern control board can be if miniature flush type instruments are used. These are available in several sizes and it is possible to obtain ammeters, voltmeters, wattmeters and power factor meters in the miniature style. The need for large instruments is often questionable, and as will be seen from the illustrations, the miniature type is extraordinarily readable.

PHASE SEQUENCE AND SWITCHBOARD INSTRUMENTS.

It is the practice of switchgear makers to arrange and connect the equipment comprising the complete switchboard on the basis of a standard phase sequence unless notified that a non-standard arrangement exists.

Lack of information where a non-standard arrangement operates leads to misunderstanding and claims that certain instruments are reading wrongly. In order that there may be uniformity in switchgear diagrams, the standard sequence has been agreed as R.Y.B. the phases coming up in that order. There are a number of variations in existence, and it is essential, if costly and annoying changes on site are to be avoided, that these variations

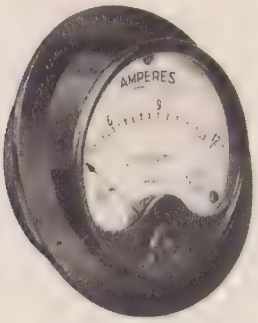


FIG. 19-14.
Miniature Ammeter with Inclined Scale
(Everett Edgcumbe & Co. Ltd.).

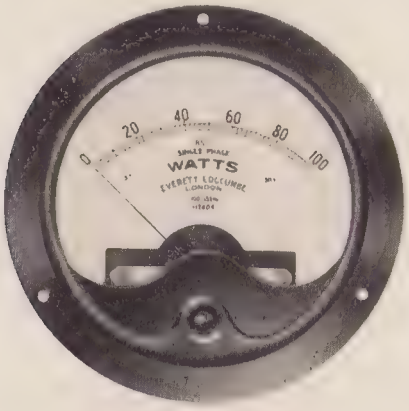


FIG. 19-15.
Miniature Wattmeter
(Everett Edgcumbe & Co. Ltd.).

FIG. 19-16.
Miniature Power Factor Meter
(Everett Edgcumbe & Co. Ltd.).

be clearly noted as between buyer and seller at the onset.

Switchboard instruments affected are those in which a definite phase relation is established between current and voltage coils. This occurs only in cases where a three-phase source is involved; those instruments (or relays) using only a single-phase source are not affected.

The following instruments and relays are those which are affected—power-factor meters, power-factor relays, phase-sequence relays, directional relays, voltage regulators with line drop compensators, distance relays.

CHAPTER XX

PROTECTIVE SYSTEMS

The simplest of all forms of protective gear is the fuse. The application of this is dealt with in Chapter XI particularly for the protection of circuits against short-circuit. The fuse apart, the cheapest form of a.c. protective gear is the direct acting overload trip with or without time lag. For the majority of industrial circuits, this form of protection is ample because rarely do problems of discrimination arise as in major networks, nor does the type demand a high degree of maintenance and of ability to choose settings in a complicated network. There is a wrong idea which still persists that discrimination can be obtained by shunting the overload trip with time limit fuses. At low values of overcurrent this may be possible, but under full fault conditions where the current value may reach 20 times normal, a series of time limit fuses of different ratings will, in all probability all operate simultaneously. As a device to give accurate time lag, the ordinary time limit fuse must be regarded as a rough and ready means. It is for these reasons that overload trips and fuses are rarely satisfactory for the protection of a.c. generators operating in parallel.

Realising the shortcomings, relay and protective gear designers have produced many devices having a high degree of accuracy and consistent operation. The most popular of these is the overload relay having inverse time/current characteristics with definite minimum time. From this stage, directional protection is but a step, adding voltage elements to the relays, and from this many systems of protection have been designed to suit different circuits and fault conditions.

Two major factors concern any protective system. They are discrimination and stability. The first is that feature which ensures disconnection of a faulty section only, leaving healthy sections free to continue supply. Stability on the other hand is that feature which ensures the ability of the protective equipment to carry through-faults without causing operation due to unbalance or other reasons by reason of the heavy currents. Tripping in this case is usually due to slight manufacturing differences in current transformers so that at all values of current the performance of each is not identical. Coupled with sensitive settings there may be a sufficiency of current to operate the relay.

There are three main circuits which demand consideration in any protective scheme. It will be convenient to deal with the forms of protection available under these headings, namely Generators, Transformers, Feeders. The separate problem of Bus-Zone Protection is outside the scope but reference to other works on this special branch are given in the Bibliography.

Generators.

It has been pointed out that overcurrent protection by means of direct acting trips, with or without time lag, is of little value for the protection of generators. The use of overcurrent relays of the inverse time limit with

definite minimum type, however, does provide some protection, particularly against *sustained* through-fault condition, busbar faults, etc. As a form of protection, however, it lacks the essential of discrimination, particularly where feeder circuits are of a capacity approaching that of a generator circuit. Where, as is more often the case, the feeder capacity is small compared with that of the generator, then some measure of discrimination is possible. Even so, the characteristics of the relay must be such that normal load, or overloads within the capacity of the machine, does not disconnect the machine from the bars.

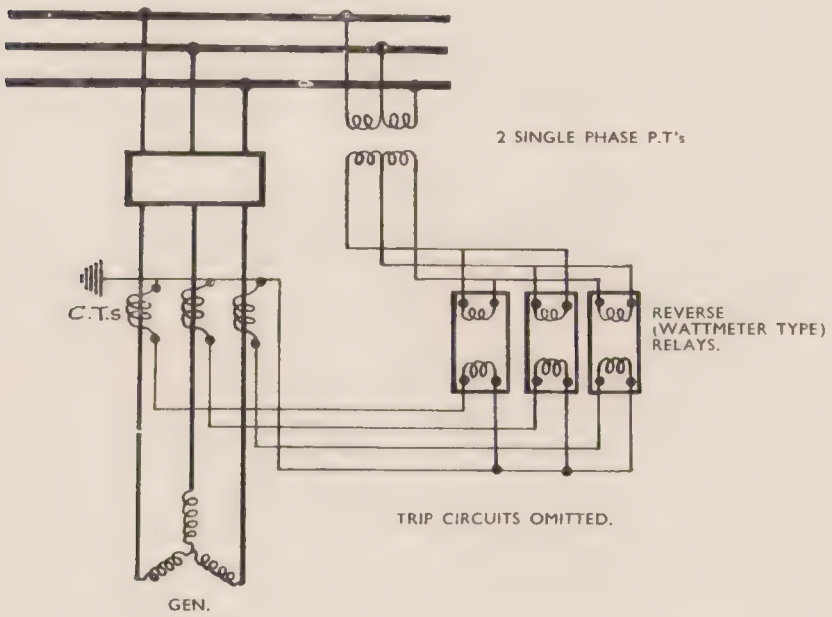


FIG. 20-1.—*Reverse Power Protection for Generator.*

Among the earliest forms of protection for generator circuits was that of reverse protection, where two or more generators run in parallel. Such protection can naturally be given settings of reasonable sensitivity, but it has been shown that reversals of power can and do take place under other conditions than those of faults within the generator. For example, system disturbances can set up reversal due to synchronous plant feeding back, and, under conditions of heavy system fault, there may be a tendency for machines to drop out of step momentarily, and be the cause of circulating power. As protection against faulty synchronising, there is something in favour of reverse protection. On the other hand, it will be clear that protection against " bad shots " is only required during the actual operation of synchronising, and therefore the better procedure is to instal a relay which is rendered inoperative after synchronising.

In the case of hand-closed circuit breakers, this can be accomplished by means of an overcurrent relay having a setting of 100% or less, and may be of the instantaneous type or of the induction type, with a short-time

setting. This relay is connected in such a way that the trip coil circuit is only complete with the synchronising plug in position. Removal of the synchronising plug renders the trip circuit inoperative. In the case of electrically operated breakers, a relay can be used which will render faulty synchronising impossible, *i.e.*, it will be impossible to close the breaker until the voltages of both the incoming and running machines are in correct relationship to each other.

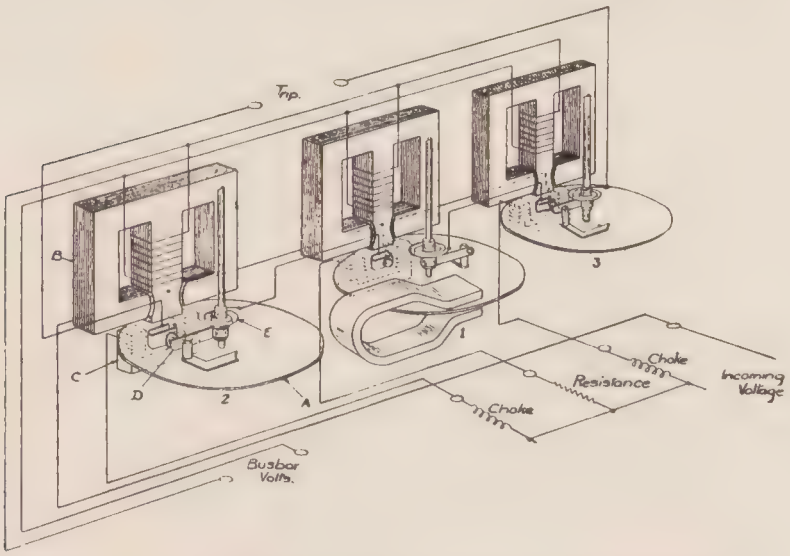


FIG. 20-2.—*Synchronising Relay for electrically operated circuit breakers* (*The Metropolitan-Vickers Elec. Co., Ltd.*).

In view of the importance of generating plant, and in spite of additional first cost, the correct form of protection to apply to any generator is that known as "Circulating Current" or "Merz-Price." Briefly, the argument may be stated as one of first cost of this form of protection against the cost of repair in the event of breakdown. The latter may be increased by revenue losses due to the failure of supply.

The differential system of protection referred to is not new. It has the virtue of being both simple and reliable and among the outstanding features of the system, the following are of importance :—

(*a*) It is discriminating, *i.e.*, it disconnects only the apparatus which is faulty.

(*b*) It is quick in action. The relays are instantaneous in action and the fault is cleared before it can develop to any serious magnitude. This has the added advantage that it avoids the overloading of other machines.

(*c*) It is sensitive and not affected by through currents. Settings are obtained well below the normal load of the machine.

The fundamental principle of differential or balanced systems of protection is that, under healthy conditions, the current entering at one end of a machine winding is identical, both in phase and magnitude, with that leaving at the other. On the occurrence of a fault this condition no longer holds and the inequality resulting operates the protective relay.

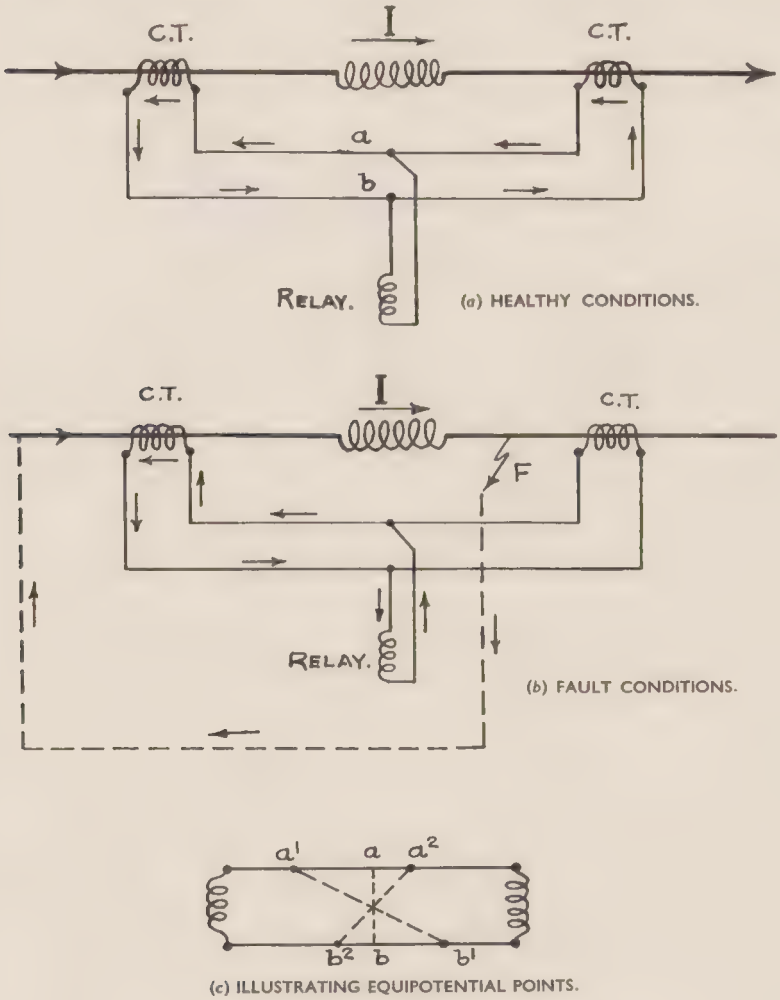


FIG. 20-3.—*Explanatory Diagram showing principle of circulating current protection.*

The circulating current principle is applied through current transformers, and these, connected as shown in Fig. 20-3, are made to have similar characteristics and ratio. The relay, as will be seen, is connected between the two pilot wires, and in order that the symmetry of the burden on the current transformers shall not be upset and thus result in an out-of-balance current passing through the relay

when not intended, it is essential to make the connection to the pilot wires at points which are equipotential under normal conditions. Such equipotential points are as those marked "a" and "b" in Fig. 20-3. In practice it is seldom possible to make this connection to the actual physical mid-point in the run of the pilots. It is usual therefore, to make the connection at convenient points and to insert compensating resistances in the shorter length of pilot wire, these resistances being adjustable to allow of exact balance.

From the explanatory diagram it will be clear that a fault *outside* the protective zone will not upset the fundamental principle of currents entering and leaving.

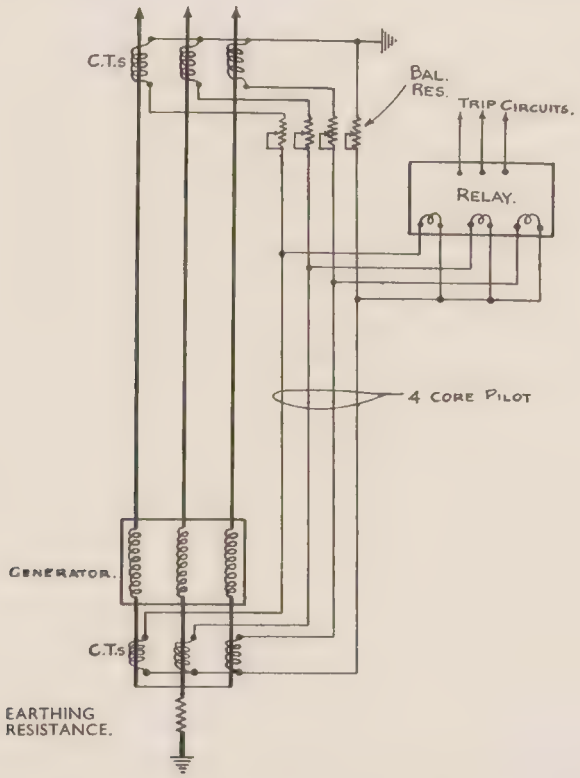


FIG. 20-4.—*Merz-Price Circulating Current protection applied to a three-phase generator.*

In its application to three-phase generators, it will be noted that two sets of three current transformers are required, one set mounted in the neutral connections and the other on the switchgear side.

These groups, each connected in star, are connected together by means of a four-core pilot cable. The relay coils are connected in star, the neutral point being connected to the neutral of the current transformers, with the outers connected one each to the other pilots.

In Chapter XXII the question of earthing the neutral point through a resistance is considered, and it is stated that in order to protect 85% of

the windings, with a relay set at 15%, the resistance should be arranged to pass full load current of the machine, or the largest machine where more than one is installed.

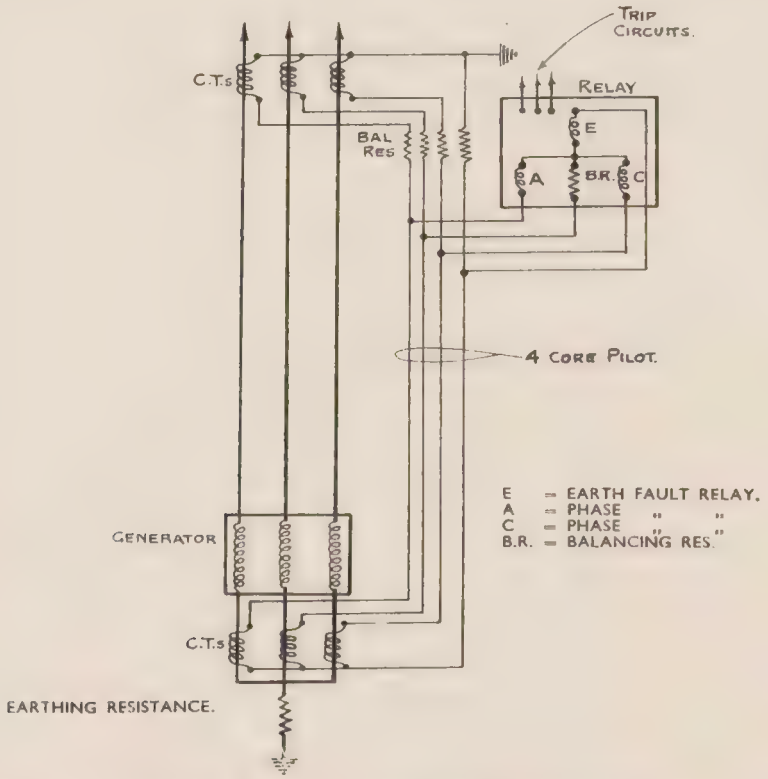


FIG. 20-5.—*Modified System of Merz-Price Circulating Current protection for three-phase generator (The Metropolitan-Vickers Elec. Co., Ltd.).*

In order to provide settings for earth faults lower than that mentioned, the Metropolitan-Vickers Company have a system of modified connections using an earth fault relay connected on the residual principle. This relay is not subject to out-of-balance currents in the event of heavy through-currents between phases, and thus it is possible to set the relay lower without fear of tripping under such conditions. In this connection it should be borne in mind that in the case of phase-fault protection, small inequalities between current transformers give rise to out-of-balance currents during through-faults, hence the need for a relatively high setting.

The type of relay used for Merz-Price protection is usually of the simple electromagnetic type for instantaneous tripping.

Reference has already been made to the use of over-current protection as back-up protection for generators.

Another condition which arises is that of single-phase, or unbalanced loading. Under such conditions, damage may occur due to heating in certain types of alternator. Standby over-current protection will normally

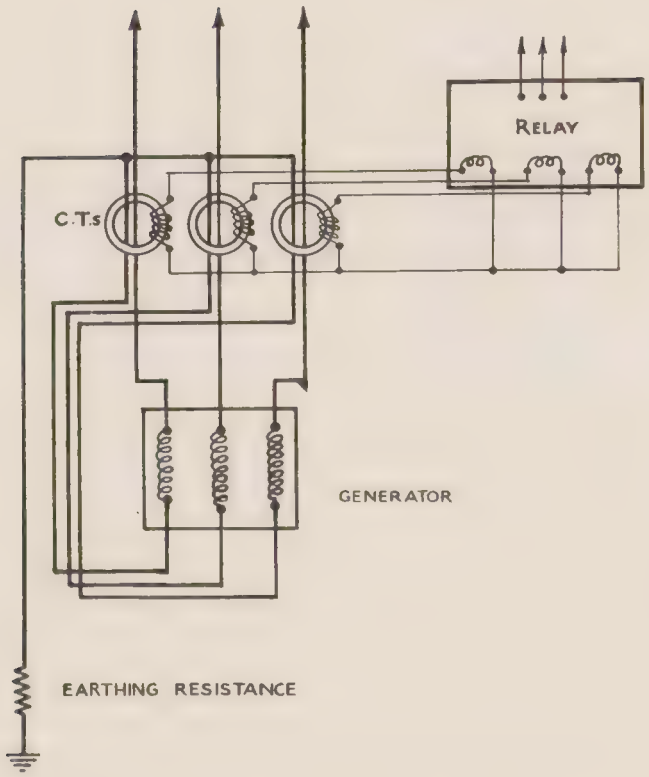


FIG. 20-6.—*Beard Self-Balancing Generator Protection.*

be set so that operation will not occur under normal load, but a single-phase current of much less value will cause excessive rotor heating. In general, manufacturers of a.c. generators will state that the single-phase loading should not be out-of-balance by more than 15%. Thus it becomes necessary, on the larger machines at least to provide a relay and connect in such a way as to be sensitive to single-phase conditions much less than full load, and yet remain unaffected by balanced load conditions.

This condition is taken care of by the introduction of a negative phase sequence relay. In the theory of symmetrical components, it has been shown that any unbalanced system can be considered to comprise three balanced systems as follows :—

(1) A three-phase system of forward phase sequence, known as the " positive phase sequence."

(2) A three-phase system of reverse phase sequence, known as the " negative phase sequence."

(3) A system without time interval between vectors, known as the " zero phase sequence."

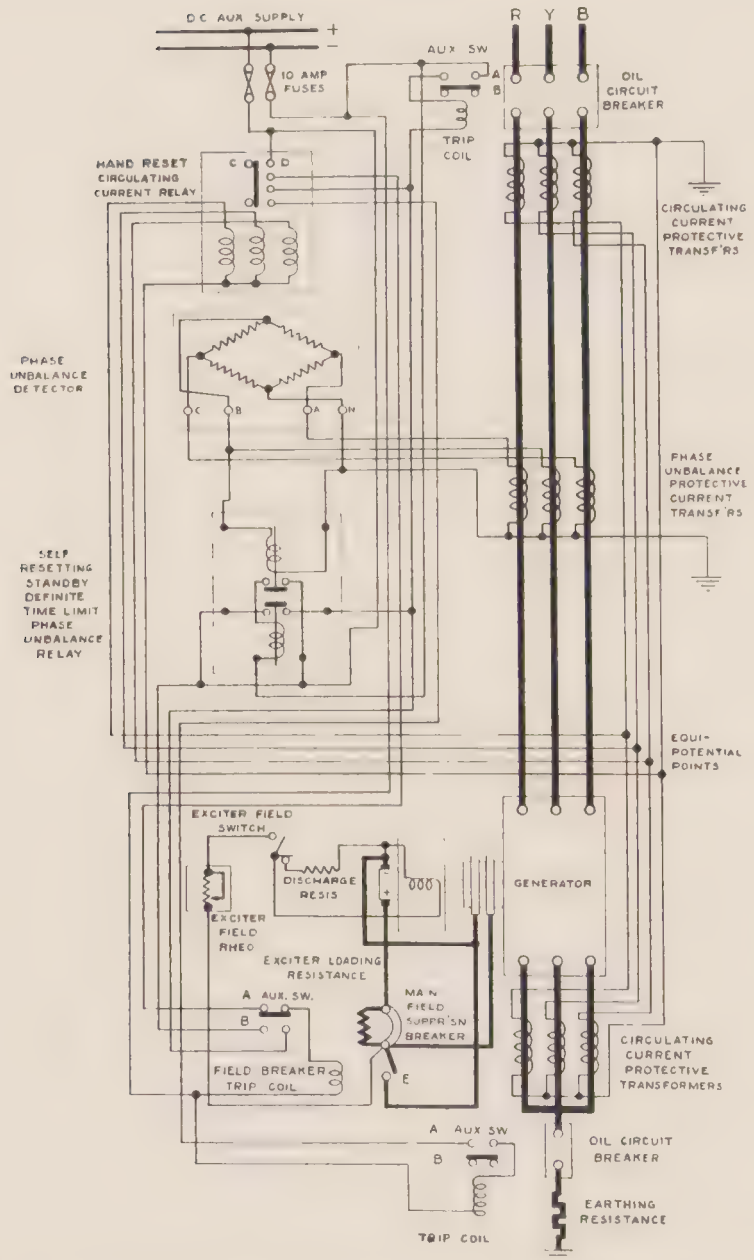


FIG. 20-7. *Negative Phase Sequence Protection applied to detect single-phase loading of a generator (The British Thomson-Houston Co., Ltd.).*

It can be shown that

(*a*) The positive component only is present in balanced three-phase conditions, and corresponds to normal load conditions.

(*b*) The positive and negative components are both present in unbalanced phase to phase conditions, and correspond to faults between lines.

(*c*) The positive, negative and zero components are all present in unbalanced phase to neutral conditions, corresponding to a line to earth fault on a system with an earthed neutral.

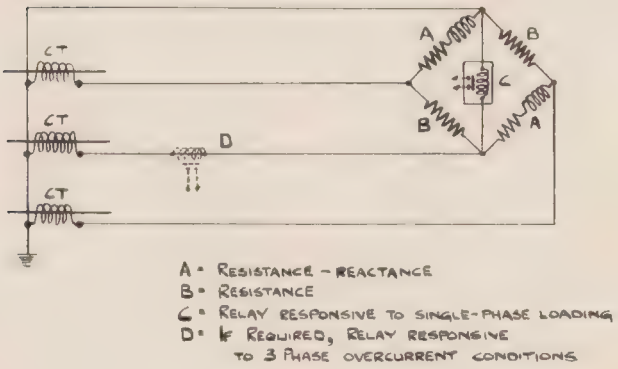


FIG. 20-8.—*Elementary Connection Diagram of Negative Phase Sequence Network.*

The negative phase sequence component is present in both conditions likely to produce unbalance in a three-phase system, and therefore a relay sensitive to this component and not to the positive phase sequence com-donent will protect the machine against conditions of single-phase loading, and can be given settings below the normal load of the generator. The circuit necessary includes not only the relay but a resistance-reactance network which acts as a phase unbalance detector. Under normal conditions no current flows in the relay windings. It will be noted that the connection follows the manner of Wheatstone bridge, and the detector is so proportioned that the current in the relay is proportional to the unbalance current.

The setting normally recommended is approximately 40-45%, with a time delay of, say, six seconds, to prevent unnecessary tripping during short duration conditions of unbalance.

The G.E.C. Biassed Differential system of protection forms an interesting example of the circulating current principle, but with a difference. This

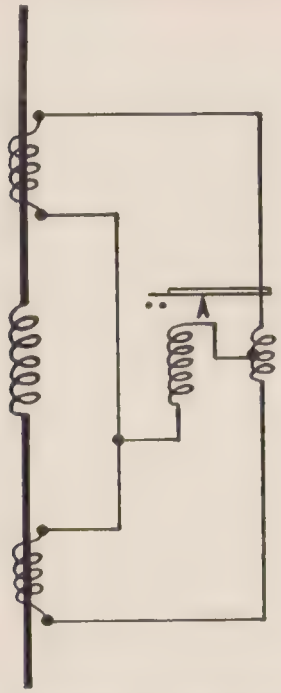


FIG. 20-9.—*Principle of protection for generator with biassed induction disc relay (The General Electric Co.).*

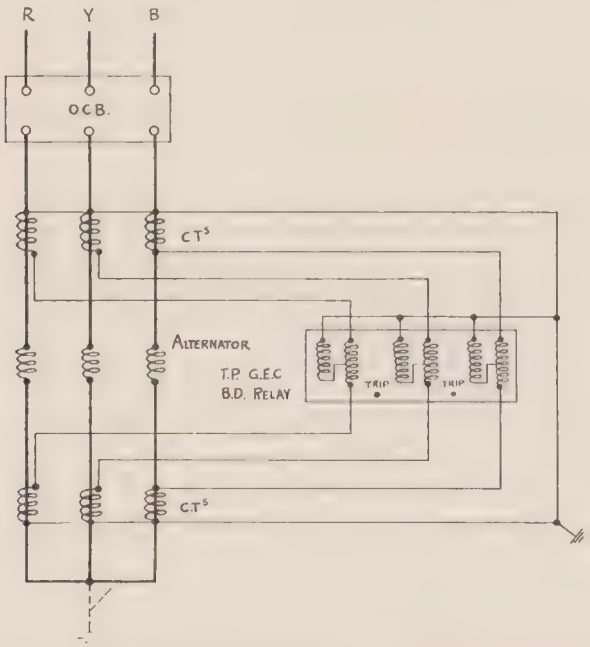


FIG. 20-10.—*Protection as Fig. 20-9 applied to a three-phase generator (The General Electric Co.).*

difference lies in the use of the biassed induction disc relay, consisting, as is shown in the single-phase diagram Fig. 20-9 of a relay with two coils, one operating, the other restraining, exerting relatively opposing torques. It will be seen that under conditions where the current leaving the winding is equal to that entering, a current proportional to the load flows round the circuit through the restraining winding. On the occurrence

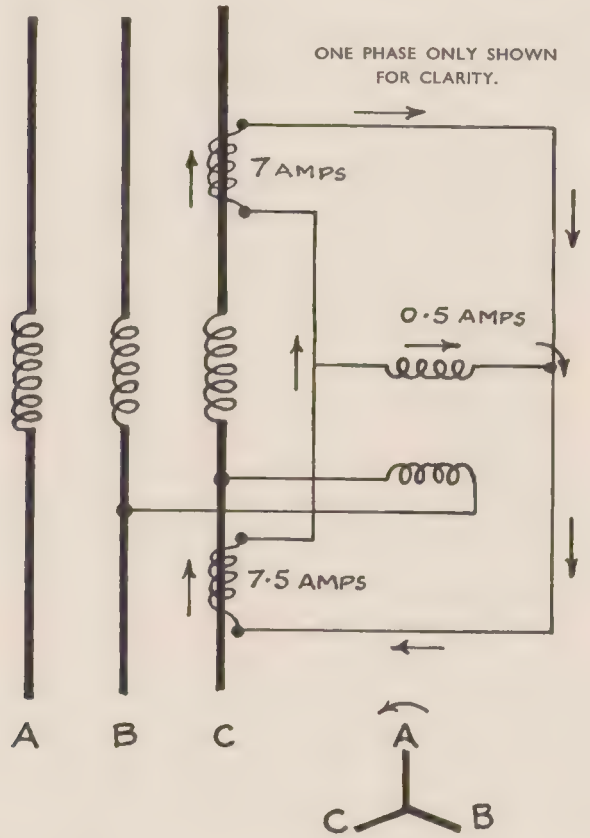


FIG. 20-11.—*Principle of Reverse Differential Protective Relay (The General Electric Co.).*

of a fault within the protected zone, excess current flows through the operating coil and when of sufficient magnitude in comparison with the current flowing through the restraining coil, the relay operates. The amount of bias is fixed by the relative number of turns in the two coils. If a five per cent. bias is required, the restraining coil is wound with 1/20th of the turns of the operating coil, and it will be evident that the relay will be held " off " until the unbalanced current flowing through the operating coil has a value equal to five per cent. of the current in the restraining coil.

A development of this protection is that which allows the relay to trip on reverse currents in addition to unbalance. Fig. 20-11 will show this modification, in which a voltage coil is connected across the phase to give a 30° lagging voltage. In this case the current transformer at the star point of the windings is wound to give a slightly lower secondary current than that at the free end. Thus a restraining difference flows continually through the relay, even when no fault exists. This current has first to be cancelled by a difference current in the event of a fault giving a bias to the scheme. In the event of a reversal the secondary current also reverses and is then in a direction to cause tripping.

It is claimed for these forms of protection that stability is obtained under all conditions.

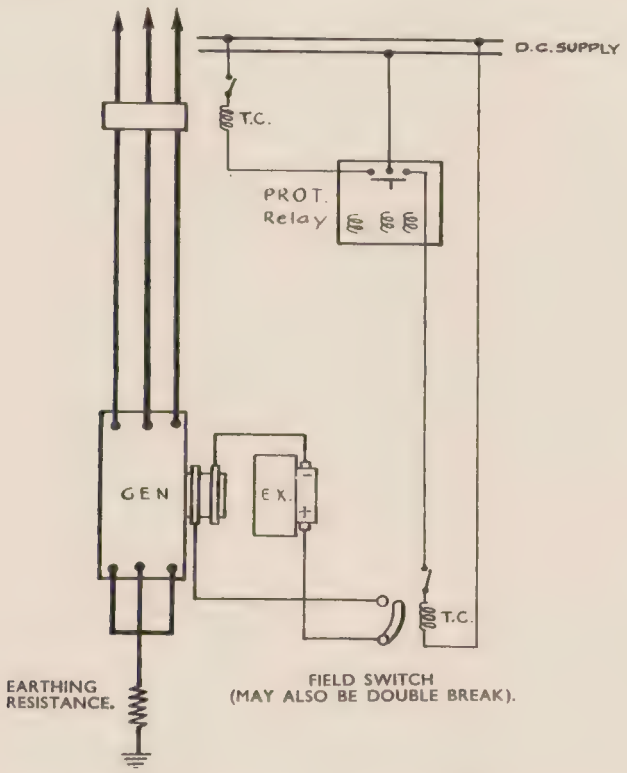
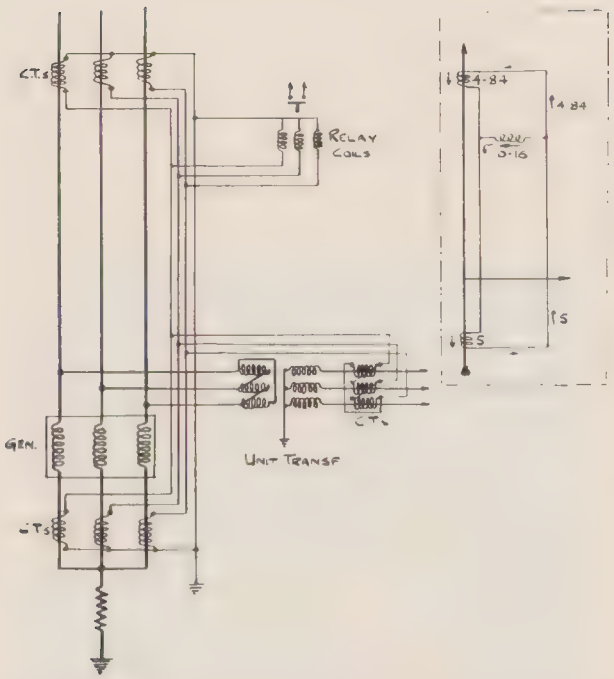


FIG. 20-12.—*Connections for Generator Field Suppression.*

It is essential in all forms of generator protective gear to prevent damage to the machine, by the suppression of the field in the shortest possible time after an internal fault has been detected by the protective gear. The usual procedure is to arrange that the field is disconnected automatically by the circulating current relay. Such disconnection does not occur on operation of the standby overcurrent relay. The most effective method is that of open-circuiting the generator field winding. This, however, results in high rotor voltages which may, in the case of built-up or laminated rotors, cause breakdown of the insulation. In machines with a solid rotor the effect



NOTE.—The inset in the above illustration shews the secondary unbalance due to a 100 kVA unit transformer tied to the terminals of a 3000 kVA generator. The current through the relay—0.16 amps.—is insufficient to trip the relay on a 15% setting.

FIG. 20-13.—*Protection of Generator with Unit Transformer.*

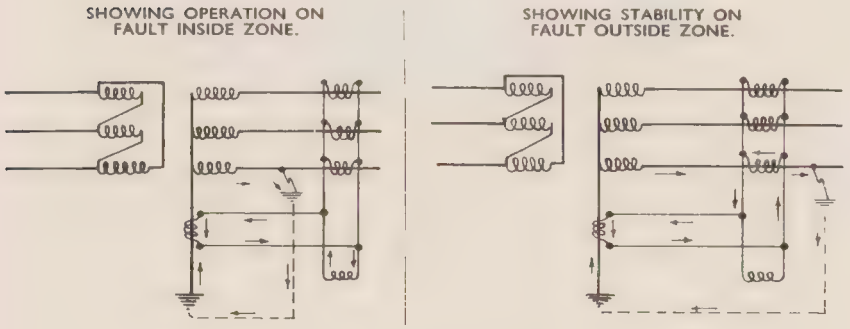


FIG. 20-14.—*Diagrams showing restricted earth fault protection for transformers.*

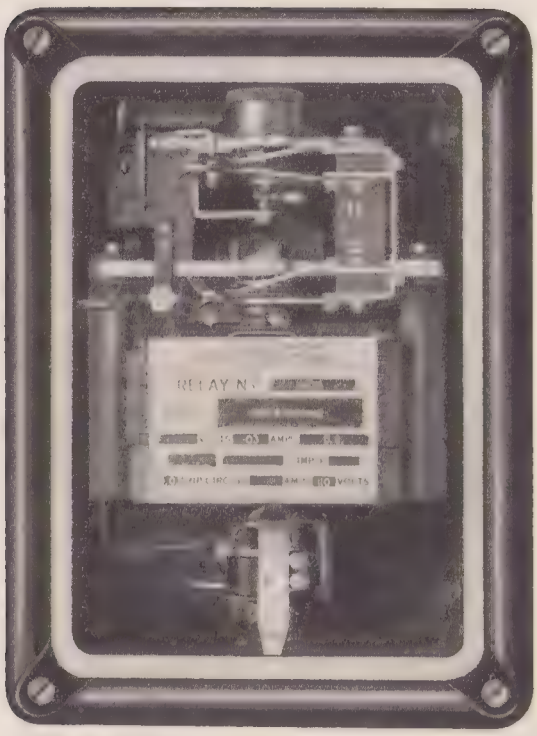


FIG. 20-15.—*Intertripping Relay (D.C.). Surge-proof to overcome interference due to induced currents under fault conditions. Inoperative with any A.C. effect. Has slight time delay to cover possibility of D.C. transients (Nalder Bros. & Thompson, Ltd.).*

is not usually dangerous, and the use of resistance is not adopted. Where resistance must be used, the suppression of the field is definitely slower. Alternative methods include the disconnection of the exciter field or the reversal of the exciter field. From the diagrams it will be clear that duplication of tripping contacts on the relay accomplish the duty of opening the field breaker, which usually takes the form of an air-circuit-breaker without blow-outs.

In certain stations, the auxiliaries appertaining to each set are supplied from what is termed a unit transformer connected directly to the free end of the generator windings, as shown. Normally, the load supplied by this transformer is constant, and only a small proportion of the full load of the generator. Accordingly it rarely becomes necessary to supply switchgear for the unit transformer as it is connected so that it is within the protective zone of the generator protection. If desired, it is a relatively simple problem to fit three additional current transformers on the secondary side of the unit transformer to summate with those covering the generator. More often than not, however, a bias can be given to the relay to take care of the difference in currents between the two sets of series transformers.

It should be borne in mind in considering the protective gear described that variations and additions become necessary in certain cases. As example, in the case of larger machines, provision is often included to

(*a*) Give alarm on occurrence of overheated windings.
(*b*) Protect against field failure by means of under-current relay.
(*c*) Give automatic closing of air dampers to eliminate fire risks.

In the case of water-wheel generators, provision must be made to prevent overspeed.

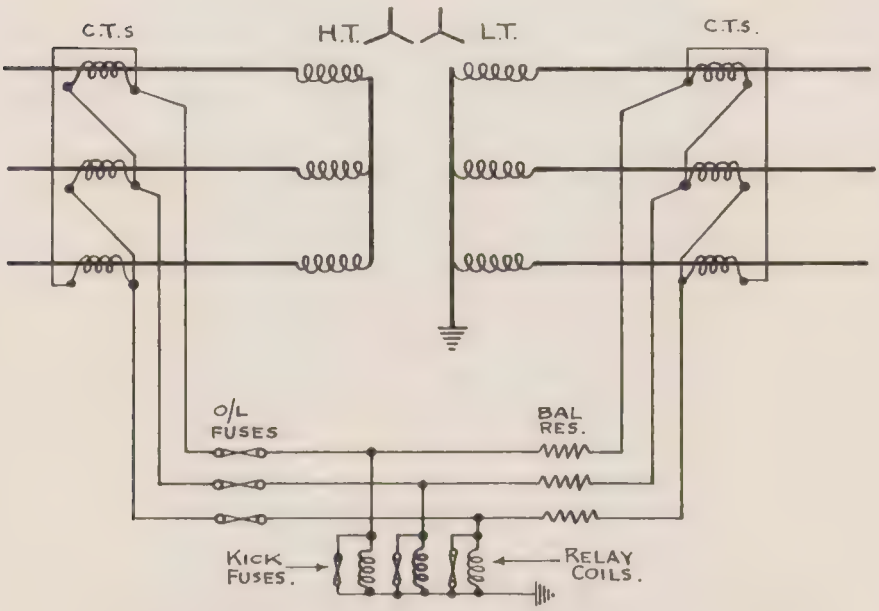
TRANSFORMERS.

In view of the large range of transformer capacities available, varying as it does from small lighting or power units of some 1 or 2 kVA, to the largest units, such as those used on the C.E.B. networks, the problem of suitable protection resolves itself into one of economics. Quite obviously it would not be possible to justify the installation of circulating current protection to a 5 kVA transformer, and in all probability the main switchgear controlling such a transformer would be of such a nature that it would be impracticable to house the necessary equipment. Nevertheless, it is appreciated that for the protection of any sizable unit, circulating current protection is desirable, or some other form such as covers both sides of a transformer as a combined unit. Examples of these other forms are those of the M.V.E. Co's Translay, the G.E.C. Biassed Differential, etc., to which reference will be made later.

For many units, plain overcurrent protection will be the form adopted. As previously stated, such protection will suffer from the disadvantage that it may operate on faults external to the transformer. Where possible, an overcurrent relay of the inverse and definite minimum type is preferred to direct acting trips with fuses. The use of an instantaneous relay is not advisable due to the possibility of operation on a switching surge.

Earth fault protection may, with advantage, be applied to both sides of a transformer. It is possible to ensure that external faults do not cause

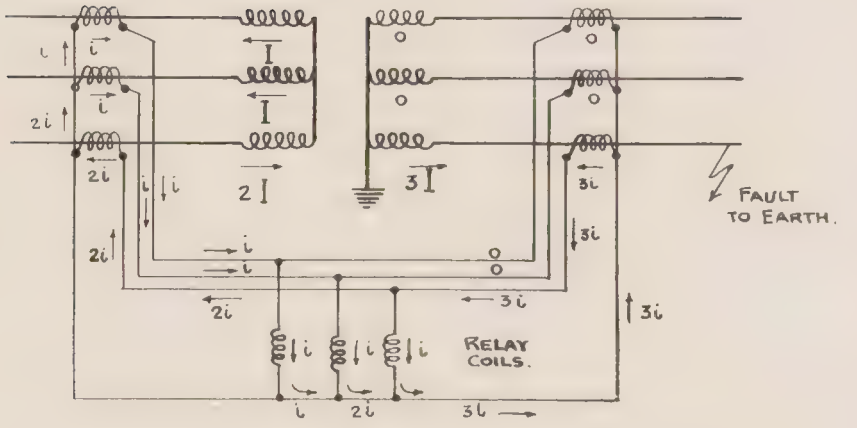
operation of the relay. In the case of the star-connected side with the neutral point earthed, a current transformer is connected in the neutral connection. The name usually given to this form is " Restricted Earth Fault " protection, indicating that it covers earth faults within a restricted area. It should be noted that an earth fault on the secondary side of a transformer affects the primary side in a similar manner to a phase fault, and thus separate relays are required to protect each winding.



NOTE.—In a Star/Star Transformer with one side having its neutral earthed, a circuit is available on that side for zero phase sequence current, while the unearthed side is an open circuit to such current. The protective CT's are delta connected, therefore, to suppress this current. If the CT's are connected star, with a common return, an unbalanced zero sequence current will flow in the protective circuit when the power transformer carries a zero sequence current due to a fault external to the transformer (see Fig. 20-17).

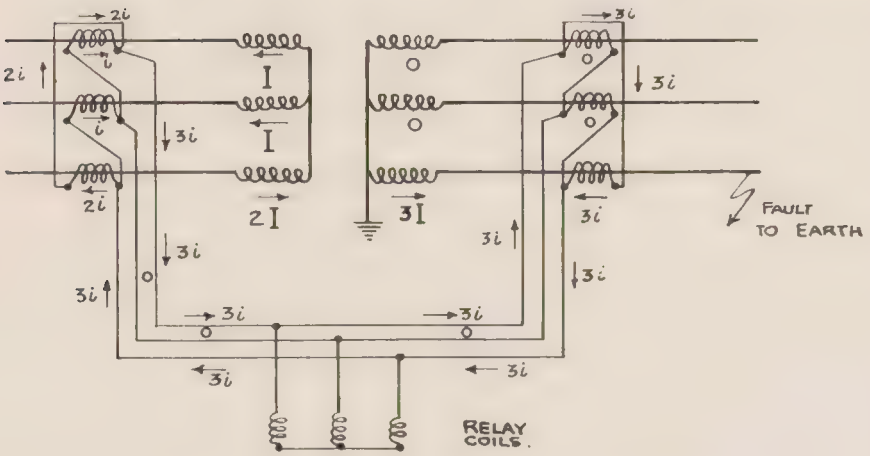
FIG. 20-16.—*Merz-Price Protection for Star/Star Transformers.*

The application of circulating current or differential protection to power transformers follows the principles discussed under the heading of generator protection, in that after allowing for differences in primary and secondary currents, those entering are equivalent to those leaving. These currents cannot obviously be equal in any mathematical sense. By suitably designed current transformers with correct ratios and connection it is possible to compare secondary currents so that they are equal under normal conditions. In the case of a star/star connected transformer, the current transformers should be connected delta on both sides. In the majority of transformers,



(*a*)

SHOWING OPERATION WHEN PROTECTIVE CT's ARE CONNECTED IN STAR AND A FAULT OCCURS EXTERNAL TO THE POWER TRANSFORMER, THE RATIO OF WHICH IS ASSUMED TO BE UNITY.



(*b*)

SHOWING STABILITY WHEN PROTECTIVE CT's ARE CONNECTED IN DELTA AND A FAULT OCCURS EXTERNAL TO THE POWER TRANSFORMER.

FIG. 20-17.—*Showing stable and unstable conditions on through faults, Merz-Price gear for Star/Star Transformer due to methods of connecting current Transformers.*

however, the more usual connection is delta/star. In such a case there is a phase displacement between the currents in the primary and secondary sides. It becomes necessary, therefore, to compensate for this in the method of connecting the current transformers. These connections are as follows :—

Current Transformers on Star Side	..	Delta Connected.
Current Transformers on Delta Side	..	Star Connected.

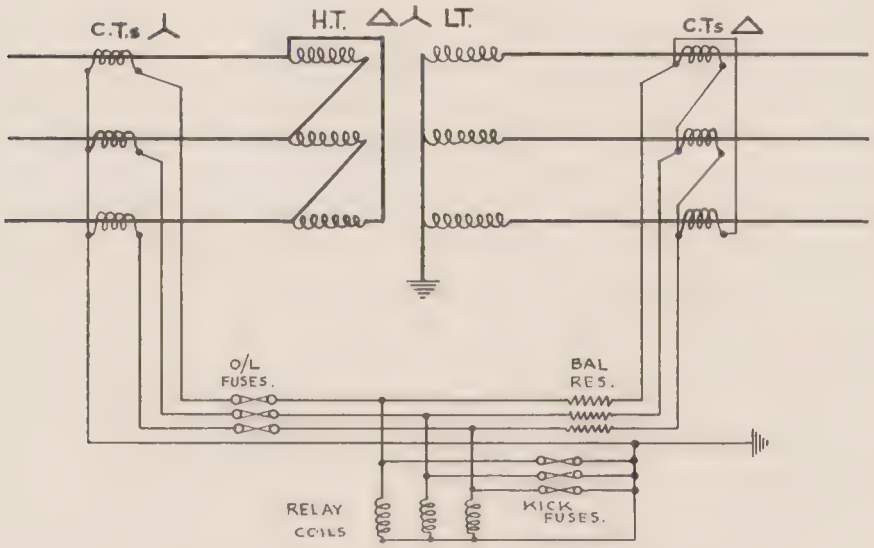


FIG. 20-18.—*Merz-Price Protection for Star/Delta Transformer.*

In choosing suitable ratios, the primary currents are, of course, those based on the kVA rating of the power transformer. The secondary current of the star connected current transformer is 5 amps., but for those current transformers connected in delta the secondary current is a delta one and must be $1/\sqrt{3}$ times, or 58% of, the star connected secondaries. The secondary current in this case is therefore 2·89 amperes.

As in the case of generator protection, balancing resistances are normally included to avoid the necessity of connecting the relay to the equipotential point on the pilot cable.

On switching in a power transformer, there is a surge of magnetizing current in the primary windings. This causes an out-of-balance which is not distinguishable, as far as the protective gear is concerned, from fault conditions. In order to prevent inadvertent operation in this way, it is usual to short-circuit the relay windings through a time-limit fuse, generally described as a " kick-fuse." Owing to its inverse time characteristic, this fuse will not blow due to switching surges, but will do so in the event of sustained out-of-balance. The installation of such fuses must clearly have its effect on the relay setting, and in order to obtain the benefit of lower settings, alternative schemes are variously used, one in which the kick fuses

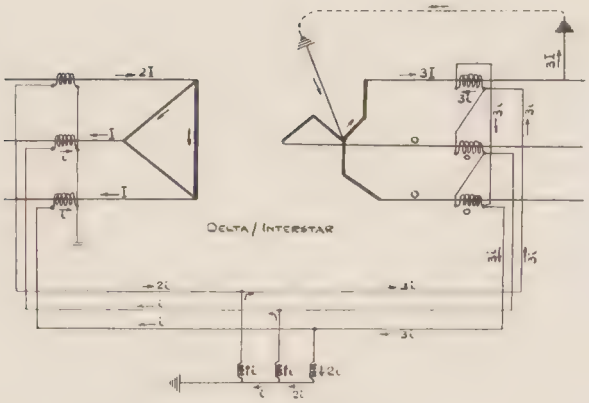


FIG. 20-19.—*Showing that circulating current protection applied to a delta/interstar transformer is not discriminating and operates on faults outside the protective zone.*

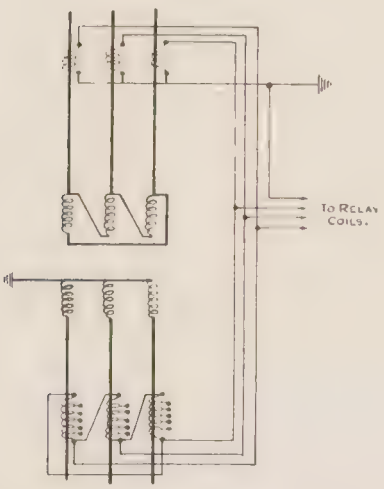


FIG. 20-20.—*Showing tappings on protective current transformers when power transformer has " off-load " tapping arrangements.*

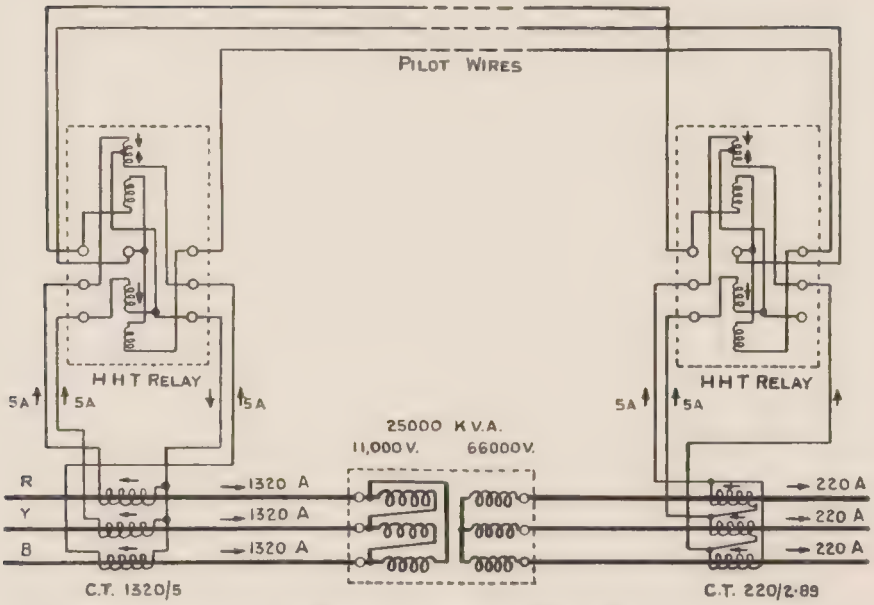
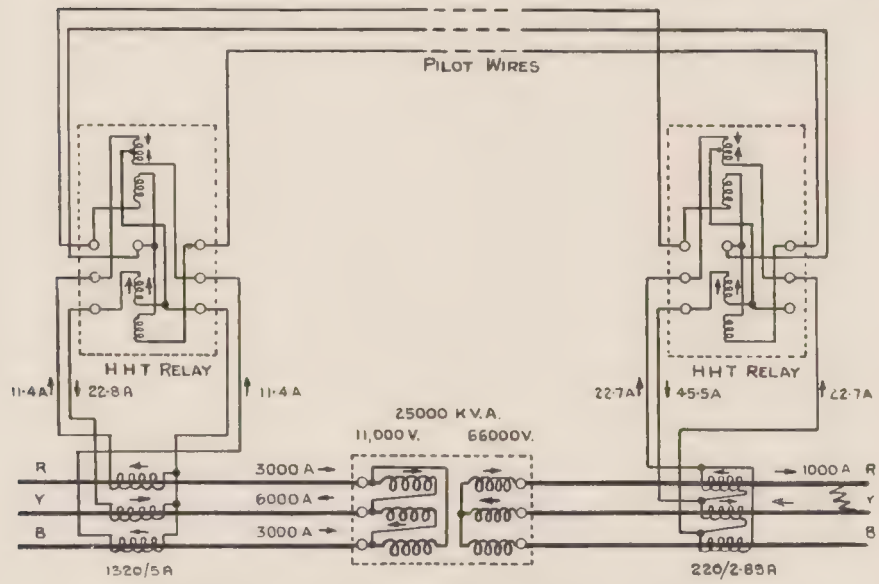


Diagram illustrating distribution of relay currents with 3-phase through load.



—Diagram illustrating distribution of relay and fault currents with single-phase through short-circuit.

FIG. 20-21.—*Translay Protection applied to a Transformer Feeder (The Metropolitan-Vickers Elec. Co., Ltd.).*

are only in circuit during the period of switching in, another in which the relay itself is of the inverse and definite minimum time type.

As in the case of generator protection, back-up overload protection may be installed with advantage, in addition to the circulating current protective gear. In the smaller units, this can be accomplished by the insertion of fuses in the pilot circuit which will blow in the event of a sustained through-fault which may result in damage to the transformer. It will be clear that, once these fuses have blown, the relay is then fed from one set of current transformers, the relay acting as an overload relay. Care should be taken to connect the relay on the *primary* side of the fuses.

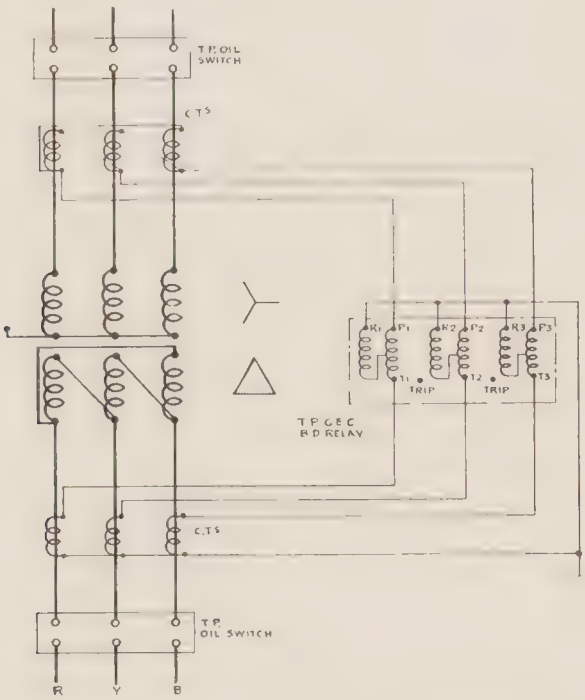


FIG. 20-22.—*Biassed Differential Protection applied to a star/delta or delta/star power transformer (The General Electric Co.).*

The tendency towards the provision of tappings on transformer windings gives rise to a complication in the application of circulating current protection. When such tappings are changed when the transformer is " off load," it is possible, by the provision of corresponding tappings on the current transformers, to change these at the same time. When tappings are changed " on-load " this is obviously not possible, and recourse must be made to a biassed scheme such as referred to earlier. In these schemes exact balance is obtained at the mean value of power transformer ratio and the system is stable on the extreme tappings.

Diagrams are included showing the Translay, G.E.C. Biassed Differential

and Magnetic Balance schemes. The complete description and theory of these demands reference to the publications of the three Companies concerned, *i.e.*, M.V.E. Co., G.E.C. and B.T.H. Co., whose specialised forms of protection they are. Briefly, for each scheme, it may be said that they are entirely suitable for use where the current transformers on primary and secondary have dissimilar characteristics, due to tappings of the power transformer, or where, due to the use of inexpensive bushing or bar primary type current transformer, these transformers may have differing ampere-turns input.

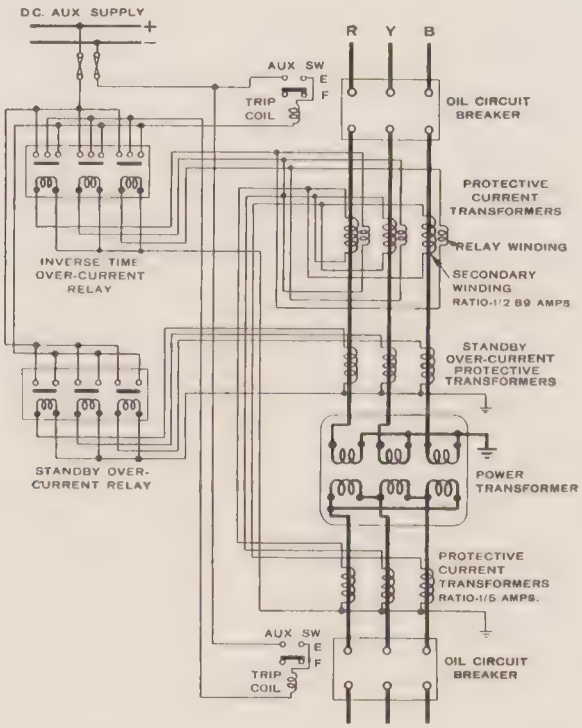
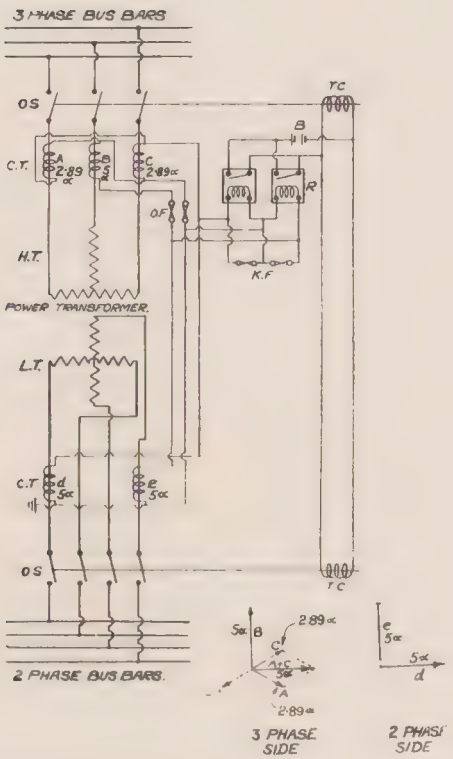


FIG. 20-23.—*Magnetic Balance Protective Gear applied to a star/delta Power Transformer, with standby overcurrent protection by separately energised inverse time induction relay (The British Thomson-Houston Co., Ltd.).*

Occasionally the necessity arises to provide protection for a Scott-connected group (Three/Two Phase).

The connections for the protection of a four-wire group are given, noting that on the three-phase side, two of the current transformers are cross-connected and have special ratios in order to obtain correct values in the pilot wires. In a three-wire group, also shown, it will be noted that on the three-phase side the current transformers are each of equal ratio, but that on the two-phase side one current transformer has a secondary current



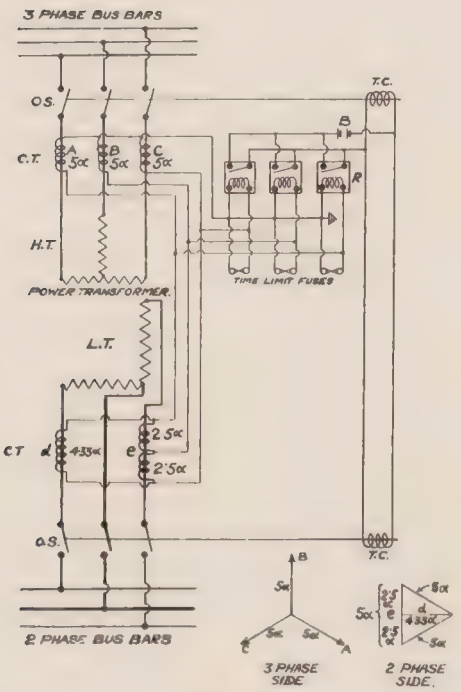
O.S.—AUTOMATIC OIL CIRCUIT-BREAKERS. C.T.—PROTECTIVE CURRENT TRANSFORMERS.
T.C.—TRIP COILS. B.—BATTERY. R.—RELAYS. K.F.—KICK FUSES.
O.F.—OVERLOAD FUSES.

FIG. 20-24.—*Circulating Current Protection applied to a Scott Connected Transformer (four wire).*

of 4.33 amperes, while on the other, outer, two current transformers with 2.5 amperes secondaries are used. The vector diagrams illustrate the above values.

In order to detect a fault in its incipient stage, the Buchholz form of protection has been used extensively on the Continent, and to some greater extent at home in recent years. In this form, a relay is connected in the pipe between the tank and conservator.

Unhealthy developments within the transformer, such as overheating, or insulation breakdown, will normally give rise to the evolution of gas. The Buchholz relay is sensitive to pressure change caused by bubbles of gas rising in the connecting pipe, and can be arranged either to give an alarm or to give both alarm and trip the associated circuit breaker.



O.S.—AUTOMATIC OIL CIRCUIT-BREAKERS. C.T.—PROTECTIVE CURRENT TRANSFORMERS.
T.C.—TRIP COILS. B.—BATTERY. R.—RELAYS. K.F.—KICK FUSES.

FIG. 20-25.—*Circulating Current Protection applied to a Scott Connected Transformer (three wire).*

Circulating current protection can be applied to combined generator and transformer units. Cases arise where it is not economical to transmit power at generator voltage owing to the location of the generating station in relation to the load centre. In the larger generating stations, it is often the practice to couple each generator to its own step-up transformer without intervening switchgear or generator voltage busbars.

The circulating current form of protection applied to combined units is shown in Fig. 20-26.

FEEDERS.

The value of suitable protective gear correctly applied to feeders cannot be overstressed. On such protective gear depends the disconnection of a

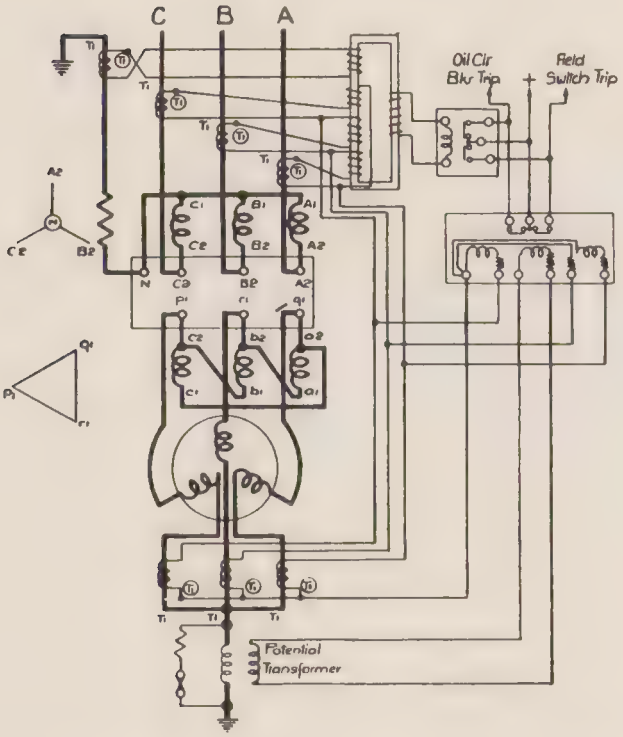


FIG. 20-26.—*Circulating Current Protection applied to a Generator and Step-up Transformer when switched as a unit, with separate h.v. Leakage Relay (The Metropolitan-Vickers Elec. Co., Ltd.).*

faulty section rather than the disconnection of feeders or sections on which the necessity does not arise.

In the case of feeder protection, the need for discrimination, already stressed in foregoing sections, is even more important.

While the forms of protection applied to the smaller generators and transformers of some years ago have been successfully applied to the larger units of to-day, the forms of protection applied to feeders have been very considerably modified and many new forms produced. This may be traced to the very rapid extension of high voltage networks, the new factors due to interconnection and, to some extent, the cost of using protection involving pilot cables over long lengths of transmission lines.

Under these changed conditions different methods were necessary. The new switching arrangements involved in the Grid network meant the wholesale reconsideration of protective arrangements.

In a book of this nature it is clearly out of the question to consider all of the problems involved; one in particular may be mentioned to further stress the problems to be faced. This is the complication which arises when, as is the case nowadays in many systems, a breaker clears a

fault at one point, then leaves the network to be fed under entirely different conditions, and in all possibility a completely different distribution of fault current, and consequently relay settings may be then inadequate to protect the system.

There are many excellent papers dealing in some detail with such problems, some of these being referred to in the bibliography.

For the purpose of this book, therefore, a brief description is given of the forms of protective gear available and some indication as to the correct point of application.

The term "feeder" is very wide; as example, a feeder may control motors, capacitors, interconnectors, ring mains. It follows that the form of protection will vary accordingly.

It will suit our purpose to consider feeders only in the sense of giving power supply to another point, at which point it may be subdivided for individual purposes.

For a straight feeder, run singly to a terminal point, the choice of overcurrent or overcurrent and earth fault protection is common. The use of an "inverse time limit with definite minimum time" type of relay provides for discrimination should any modification be made later involving feeder sections. A wide range of settings is possible, while maintaining at all times a predetermined definite minimum time under fault conditions. This type is available in both directional and non-directional types, the former including the induction overcurrent element of the latter with the addition of a sensitive watt-meter element (the directional element).

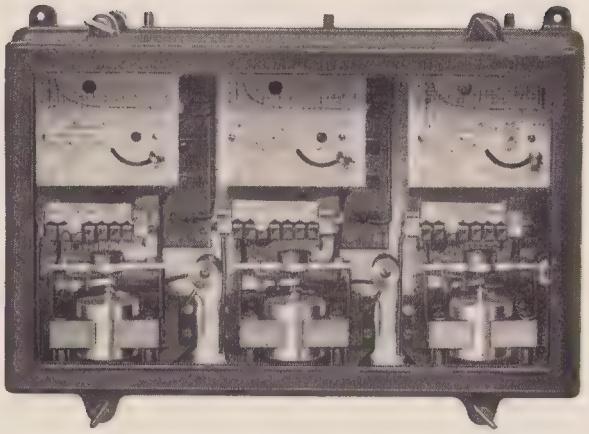
From the simple dead-end feeder, the next steps are to parallel feeders, parallel feeders with tee-off, and ring mains.

In the case of parallel feeders with one source of supply, overcurrent, or overcurrent and earth fault can be applied simply by installing non-directional relays at the source of supply, and directional relays at the receiving end. From Fig. 20-28 it will be apparent that should a fault occur on Feeder 2 as indicated, this is fed directly from the source by Feeder 2 and indirectly from Feeders 1 and 3. Under these circumstances, both circuit breakers on Feeder 2 will be opened, leaving Feeders 1 and 3 in service. Clearly, the circuit breakers at the receiving ends of Feeders 1 and 3 cannot open as the direction of fault feed is opposite to the operating direction of the relays. The relays at the supply end of these feeders, being non-directional, will commence to operate, but, owing to the lower value of fault current (divided between two feeders in parallel) will take considerably longer to complete operation than the relay in Feeder 2. It is not within the scope of this chapter to consider the distribution of fault currents under such circumstances, but it can be shown that this will be such as to ensure, due to the relay inverse characteristics, that the relay at the source in Feeder 2 will operate before those in 1 and 3.

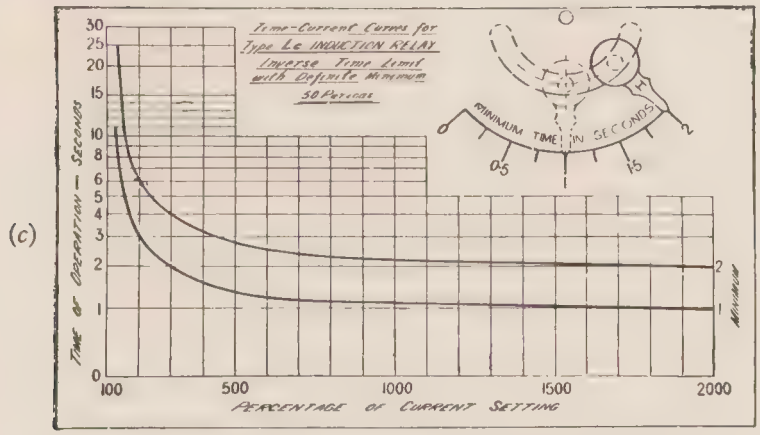
The application of similar relays to parallel feeders with a tee-off follows similar lines to the above, as will be seen from Fig. 20-29.

It is perhaps on a ring main that relay protection of the type described is best applied. In any ring main, and for the moment avoiding complication by interconnecting two points across the ring or the linking of two ring mains, there is a source of supply and a ring cable off which is tapped a number of substations. The usual diagram for such a ring main is given and includes the usual symbols to indicate non-directional or directional relays, *i.e.*, a double-headed arrow for non-directional and a single-headed

(*a*)



(*b*)



(*c*)

FIG. 20-27.—*Typical Overcurrent Relays and Time Current curves showing definite minimum characteristics.*

(*a*) *Vertical Pattern Non-directional Relay.*
(*b*) *Horizontal Pattern Directional Relay.*
(*c*) *Time Current Characteristic Curves.*

Curve 2—Relay set at 2 secs. def. min.
Curve 1—Relay set at 1 sec. def. min.

(*Nalder Bros. & Thomson, Ltd.*).

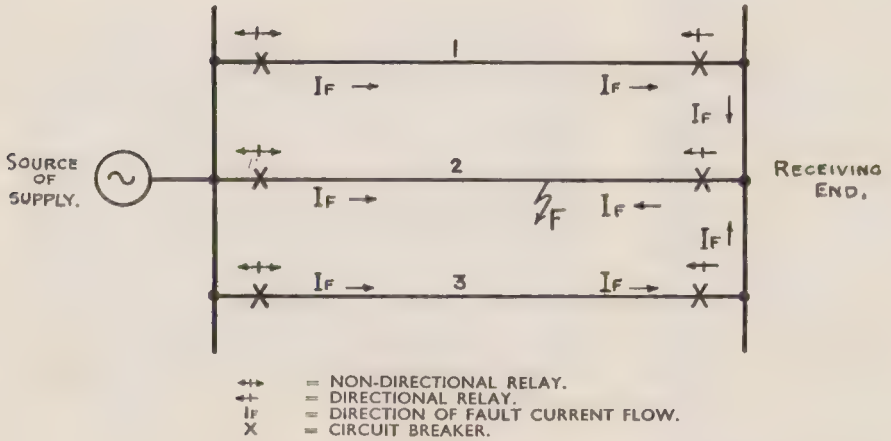


FIG. 20-28.—*Application of directional and non-directional relays to parallel feeder protection.*

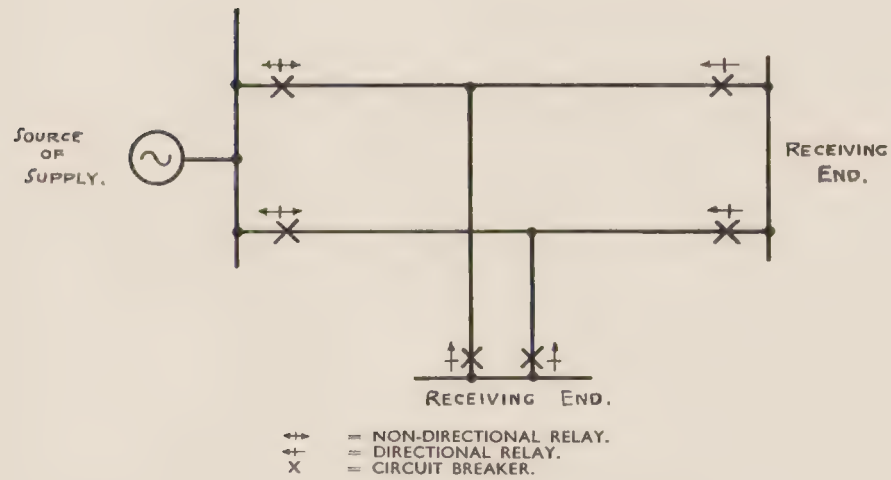


FIG. 20-29.—*As Fig. 20-28, but with tee-off feeders.*

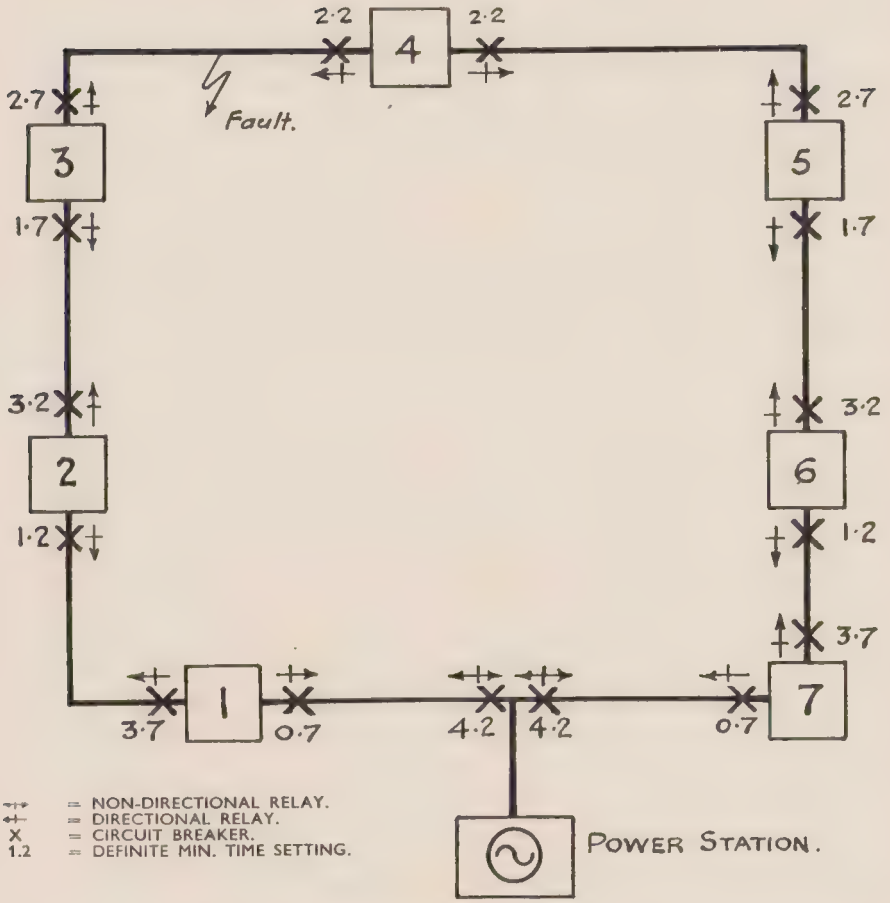


FIG. 20-30.—*Typical Ring Main Scheme showing application of directional and non-directional relays to give discriminating protection.*

arrow for directional. It will be clear that in the case of the single-headed arrow, the arrow points the direction of flow of fault current to operate the relay.

At the source of supply, a non-directional relay is applied. At each substation, a directional relay is applied such that it will operate when fault current flows *away* from the substation. It is one of the essentials of a ring main scheme that supply shall be maintained even though a section of cable breaks down. Thus, if it is assumed that a fault occurs on the cable between substations 3 and 4, only the circuit breakers at the ends of this cable shall open, and therefore, in spite of the faulty cable, each substation is given supply. That this discriminative operation does occur will be clear from the following :—

It will be noted that at the side of each relay, a figure (*e.g.*, 1·2) is given.

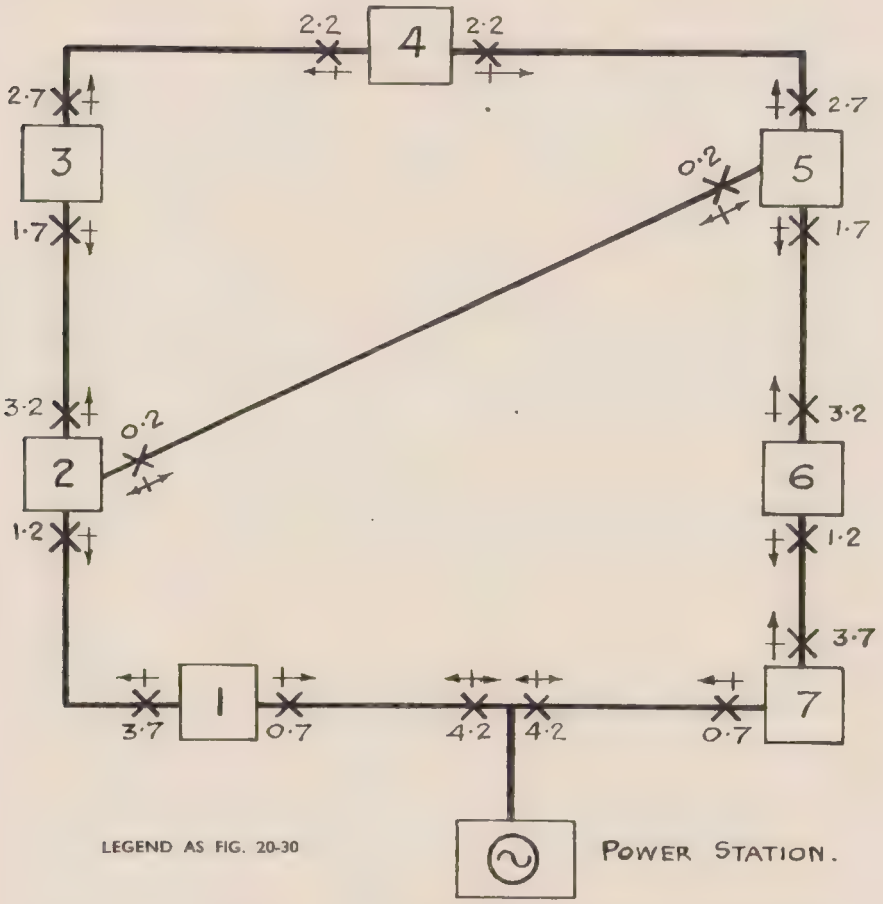


FIG. 20-31.—*As Fig. 20-30, but including a tie between two substations.*

This represents the selected definite minimum time setting of the relay, and it will be noted that, starting from the source of supply in either direction, the *outgoing* relays are regularly reduced in value.

Following out now the functioning of the relays under the conditions of assumed fault between substations 3 and 4, we find that feeding to the left hand, the relays on the outgoing sides of the power station and of substations 1, 2 and 3, will operate in the definite minimum times of 4·8, 3·7, 3·2 and 2·7 seconds respectively. It follows that the 2·7 second relay will clear the fault in this direction, and that the breakers at the Power Station and Substations 1 and 2 will remain closed. Feeding to the right hand from the power station and through substations 7, 6, 5 and 4, the relays on the outgoing sides have times of 4·2, 3·7, 3·2, 2·7 and 2·2 seconds respectively, thus ensuring the opening of the outgoing breaker at substation 4, before those at 7, 6 and 5 and Power Station.

In the example chosen, relays having a range of four-seconds have

been used. Two-second relays will be found sufficient, except where more than five relays have to be graded. In general, the interval between successive relays is of the order of 0·5 second.*

As a further example, we may assume a similar ring main but with a tie between substations 2 and 5. In so far as the ring main is concerned, no change is necessary. For the tie, it will be noted that non-directional relays are used.

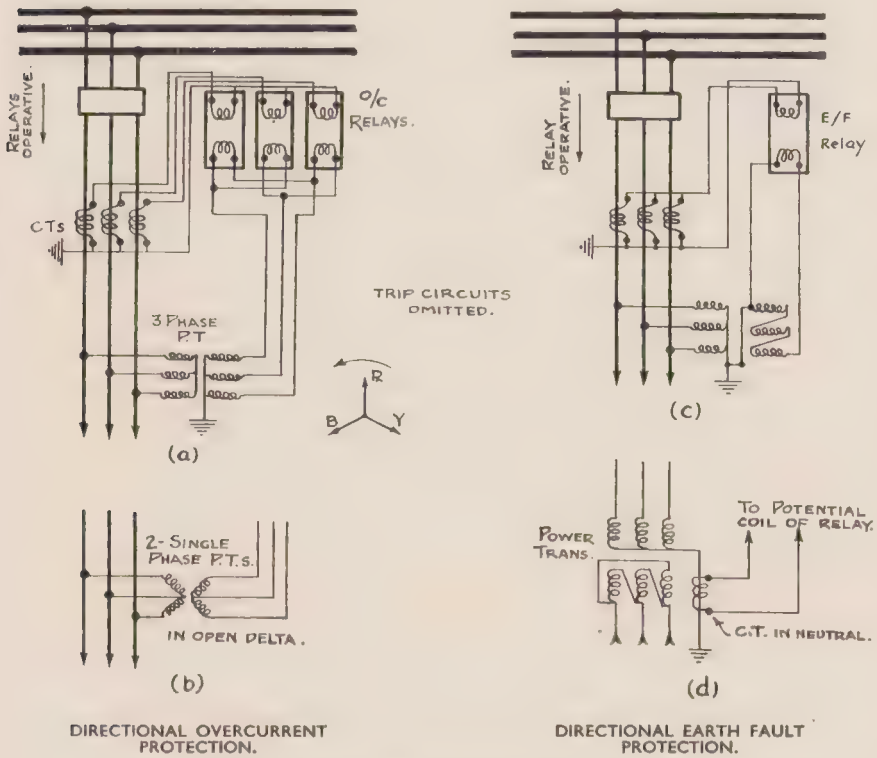


FIG. 20-32.—*Illustrating methods of obtaining source of potential for directional relays.*

For non-directional relays, three current transformers only are necessary. In the case of directional relays, however, it is obviously necessary to instal a voltage transformer. When required for directional earth fault protection, this should be of the three-phase shell type or three single-phase transformers connected in star. In this case the voltage coil must be energised from a voltage corresponding to that of the faulty phase, a condition not obtained in the core type (see Chapter XVIII).

The accompanying diagrams illustrate the various methods, both for directional overcurrent and earth fault protection. In noting the use of two single-phase voltage transformers connected in open-delta, it should

* *See Chapter XXI.*

at the same time be noted that this arrangement is limited, as in other forms of protection yet to be described it is essential to have the neutral point available.

Having described the simple application of overcurrent and earth fault protection, some consideration may be given to other forms. Due recognition must be given to the fact that as systems become more involved and complicated, so the application of satisfactory protection by simple means recedes. Thus new forms have been evolved to cope with these complications.

Of the forms to be described, some are quite old, such as split-conductor, balanced voltage, etc. Of the new ones, such as Translay, Split Pilot, Solkor, these may be said to be products of the " Grid " period and have been tried and proved in service.

In selecting any scheme, due consideration must be given to many factors. Of these, the necessity or otherwise of pilot cable is important. The cost of such cables on a long line is high, and may be prohibitive. Further, on an existing line, the introduction of pilot cables may be an impossibility. In other cases, pilot cables can be telephone pairs often existing between stations.

The various forms of feeder protection will be described under headings as follows :—

Circulating Current.
Balanced Voltage (Merz-Price and Beard-Hunter).
Split Conductor (Merz-Hunter).
Parallel Feeder (excluding special systems).
Group Feeder.
Translay.
Impedance (Distance).
Self-Compensating.
Split Pilot.
Solkor.

Circulating Current.

The circulating current form of protection to be described is that of the General Electric Co., Ltd.

As in the case of this Company's protective gear described for generators and transformers, the biassed beam relay is used. It involves the use of pilot cables from end to end of the feeder and two arrangements are possible, using three and two pilots respectively. In single phase form, it will be seen that the current transformers are connected to the pilot wire through the restraining coils of the induction disc relay. At each end there is what is termed a " dummy " circuit consisting of the operating coil, and a duplicate resistor, the latter having a resistance equal to one-half the resistance of the pilot wire. Thus, two alternative paths are provided for the secondary current.

While, therefore, the pilot circuit has twice the impedance of each " dummy " circuit, it also has two current transformers in series to drive the current through it, as compared with only one for each dummy circuit. The current divides equally between the two circuits under healthy conditions. The windings of the operating and restraining coils are identical, but the torque from the restraining coil is arranged to be greater so as to bias the disc to the " off " position.

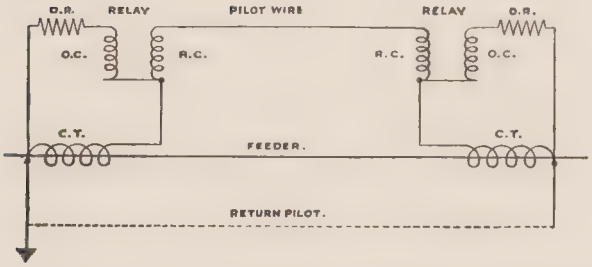


FIG. 20-33.—*Single-phase schematic diagram of Biassed Differential Protection for feeders or interconnectors (The General Electric Co.).*

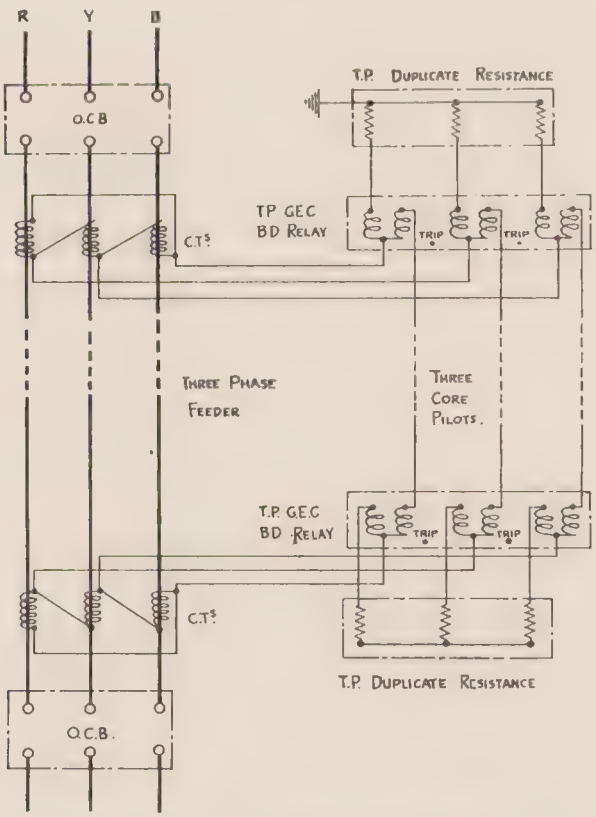


FIG. 20-34.—*Three-Phase Application of Fig. 20-33 (The General Electric Co.).*

A fault on the feeder produces inequality of currents as between transmitting and receiving ends. The excess current at the transmitting end still has two paths open to it, but that through the operating coil has now only one-third the impedance of the second path, which includes the two restraining coils and the duplicate resistor at the receiving end. Thus, operation of the relay is caused by three-quarters of the excess current passing through the operating coil and one-quarter by the alternative path.

Applied to a three-phase line, the diagram repeats the equipment as above three times, and is connected as shown, with a three-core pilot cable. By a sacrifice of sensitivity, a two-core pilot, with a single relay at each end, will give complete protection.

It is claimed for this scheme that it is not affected by capacity currents; a defect in balanced voltage schemes necessitating screened pilots. Consideration of the diagrams will show that capacity currents flow through the restraining coils only, thereby giving additional restraint against operation.

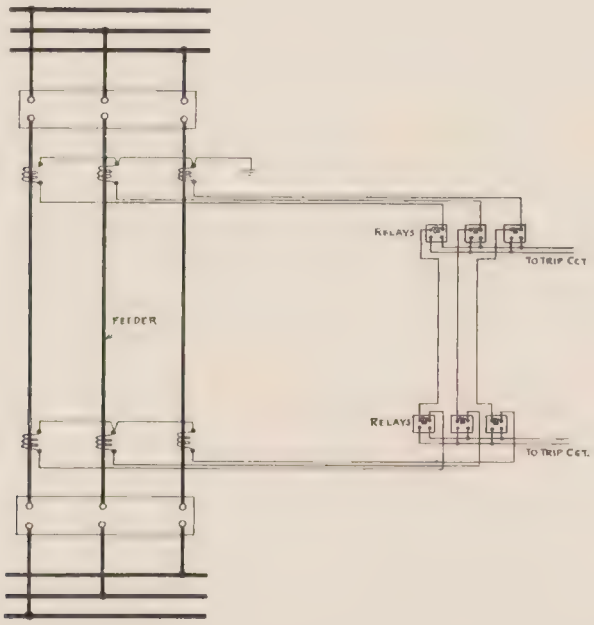


FIG. 20-35.—*Merz-Price (Balanced Voltage) Protection for Feeders.*

Balanced Voltage (Merz-Price and Beard-Hunter).

Another scheme involving the use of pilot cables. In its original form, capacity currents on long lines were a source of trouble, these often being of sufficient magnitude to trip the circuit unless high settings were adopted.

As will be seen from the diagram, the Merz-Price scheme involves a triple pole relay and three current transformers at each end of the feeder. Normally no current flows in the pilot wire, the secondary voltages being balanced against each other. A fault anywhere along the protected zone trips the breakers at both ends.

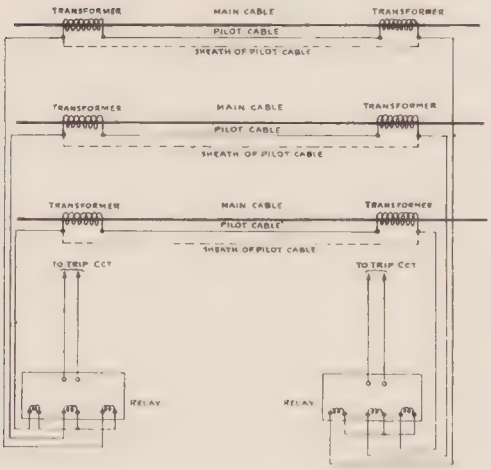


FIG. 20-36.—*Beard-Hunter (Balanced Voltage with screened pilots) Protection for Feeders.*

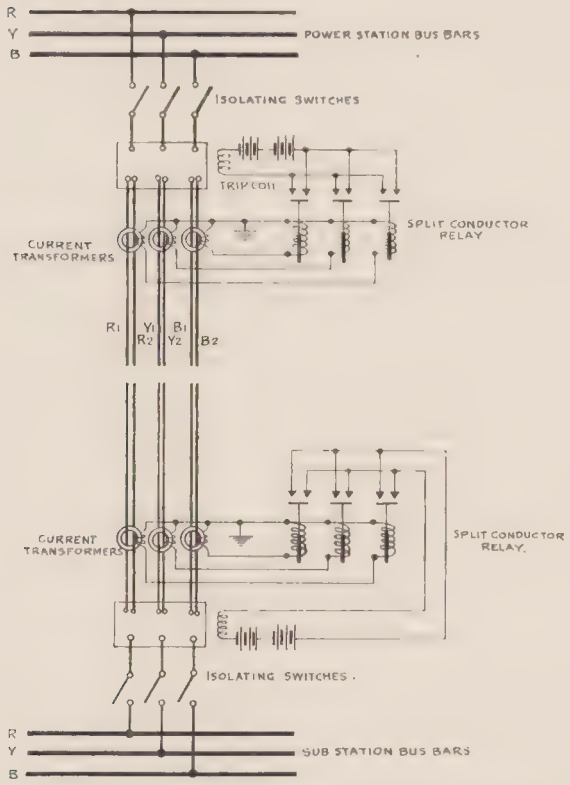


FIG. 20-37.—*Split-Conductor Feeder Protection.*

Specially balanced current transformers are necessary to obtain stability on through faults.

In the Beard-Hunter scheme, similar equipment is used as in the Merz-Price, except that in this case a metal sheath surrounds each core of the pilot cable. This sheath intercepts the capacity current flowing from the pilot cable to earth. The sheath must be divided at the centre of the cable to form two separate conductors of equal length. Naturally, the cost of the pilot cable with this scheme is increased.

Split Conductor (Merz-Hunter).

This scheme is an excellent one with only one defect—it involves the use of a split conductor cable which includes two equal cores per phase, and a special oil circuit-breaker with split contacts. Under normal conditions the current in each phase divides equally in the two cores, which are insulated from each other. In the event of a fault, this current balance is upset, and, noting that the two primary windings of the special current transformer oppose each other, a current proportional to the unbalance energises the relay.

The necessity for the split contact breaker is as follows:

Assume a fault very close to one end of the feeder. The current transformer at the faulty end will have a much greater out-of-balance than that at the remote end, which supplies current through two paths of almost equal impedance. With the split contact breaker it will be seen that the breaker at the faulty end having opened, there is no danger of that at the remote end remaining closed, as the paths have now been opened throwing complete out-of-balance on the remote transformers.

Parallel Feeders.

Where two or more feeders feed from a common busbar at one point to common busbar at another point, such feeders can be protected by a system of relays working on the simple principle of comparing currents. So long as balance is maintained, the relays will be inoperative, but on the occurrence of a fault in any one, the balance will be upset and the faulty feeder disconnected.

Using differential relays, this method can be applied to two or three feeders in parallel. Under the description of "Translay" protection, reference will be made to a system suitable for a larger group of feeders.

In nearly all cases, the system will comprise a transmitting end and a receiving end. In other words, the source of power is from the transmitting end only. Under these circumstances, a non-directional relay can be used, with a directional relay at the receiving end. The elementary diagram (Fig. 20-28) will show that in such a scheme, whereas power can only be fed in one direction at the transmitting end under both healthy and fault conditions, the direction of feed at the receiving end is reversed under fault conditions in the faulty feeder, thus involving the use of a directional relay. It will be noted also that even though the currents at the receiving end are reversed in relation to each other, they may yet be equal. The sensitive directional element, however, trips out the breaker at the receiving end of the faulty feeder, leaving the fault to be fed by one feeder only from the transmitting end, which in turn is disconnected. As in the case of split conductor protection, it will be seen that if a fault occurs at a point very near to the receiving end, this fault is fed by two paths of almost equal impedance and the difference in currents may be insufficient to trip the

breaker at the transmitting end. The operation of one breaker at the receiving end as described above, however, produces complete unbalance and consequent disconnection.

In the case of a system where either end may be the transmitting end and either end the receiving end, then directional relays must be applied at both ends.

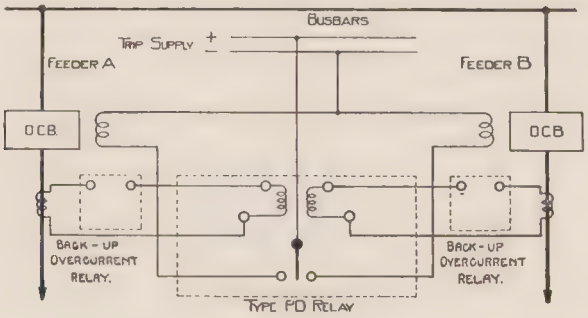


FIG. 20-38.—*Single Line Diagram showing differential parallel feeder protection, non-directional for transmitting ends. Type PD relays (The Metropolitan-Vickers Elec. Co., Ltd.).*

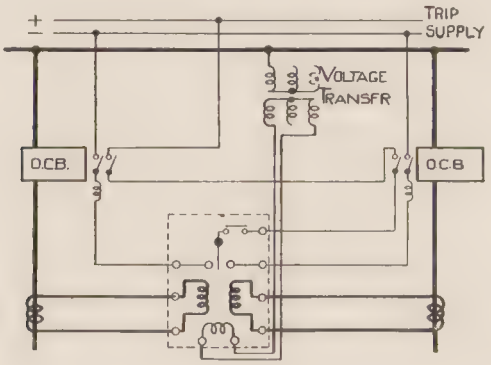


FIG. 20-39.—*Single Line Diagram showing differential parallel feeder protection, directional for receiving ends or where there is more than one source of supply. Type ND relays (The Metropolitan-Vickers Elec. Co., Ltd.).*

Typical diagrams are included illustrating the use of both types. It will be noted that for two parallel feeders, one triple pole relay only is required at each end. For three feeders, three triple pole relays are necessary.

Where there is no limitation placed on the value of earth current which can flow, phase fault relays will be sensitive enough to give protection on earth faults.

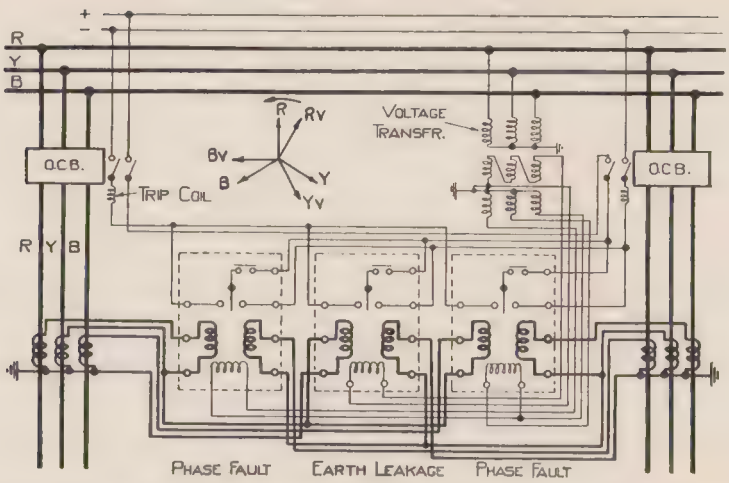


FIG. 20-40.—*Three-Phase application of Fig. 20-39, showing phase and earth fault type ND relays (The Metropolitan-Vickers Elec. Co., Ltd.).*

Where earthing resistances are used to limit the value to less than twice the current of the primary rating of the current transformers on the largest feeder, the earth fault relay should be used with two phase fault relays. The earth fault relay will be connected on the residual principle.

One difficulty arises in parallel feeder protection, that of protection when one feeder is out of commission, either deliberately or due to fault conditions.

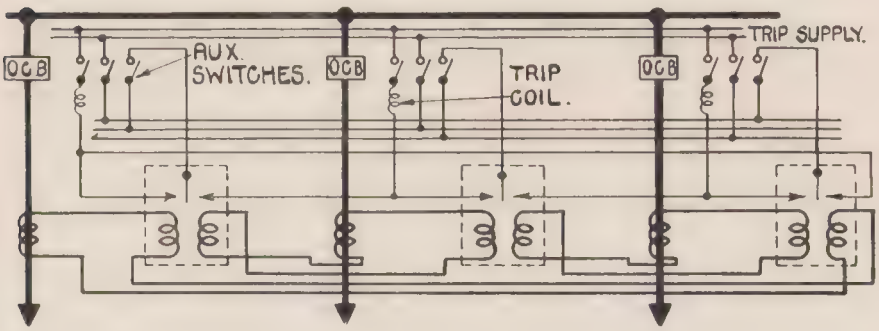


FIG. 20-41.—*Connections for three parallel Feeders using Type PD relays (The Metropolitan-Vickers Elec. Co., Ltd.).*

For this reason, the feeders must be equipped with back-up overcurrent protection usually of the type described earlier, *i.e.*, inverse time witv definite minimum—and each circuit breaker is fitted with an auxiliary switch which renders the differential protection ineffective after one feeder of a pair is taken out of service, leaving the service feeder protected by overcurrent. In the case of three feeders, the disconnection of one will leave the other two covered by differential protection.

In order to prevent wrong operation of the relays, it is essential when taking a feeder out of service under normal switching conditions that the breakers at both ends are opened.

The differential relays used are of the induction type, wherein the disc is caused to turn under the influence of two electromagnets. Connected as they are to current transformers in two circuits a balance is maintained under healthy conditions. Under fault conditions the disc turns in a direction determined by the coil carrying the greater current. Duplicate tripping contacts are fitted as illustrated in the diagram to open one or other of the breakers. The relays are suitably biassed to ensure stability on through faults.

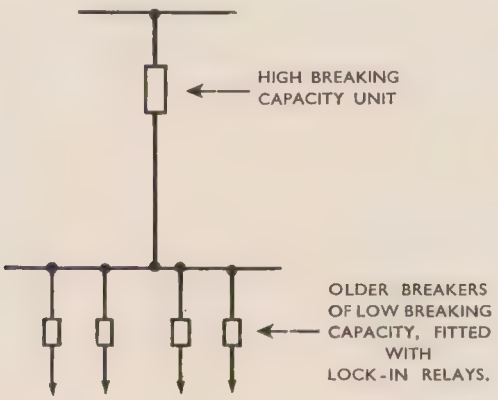


FIG. 20-42.—*Group Feeder Protection.*

Group Feeders.

It is often found that while it is necessary to retain a number of breakers installed at an early date, the maximum short-circuit current has grown beyond the capacity of those breakers. In certain cases this can be taken care of by the installation of one large breaker of adequate capacity, this breaker acting as a group feeder controlling a number of the smaller breakers. This arrangement is shown in Fig. 20-42, but to be of value, it is essential that protective gear be applied which will ensure the larger breaker taking care of faults beyond the capacity of the smaller breakers.

To this end, each of the smaller breakers must be fitted with a lock-in relay, such as the Metropolitan-Vickers Type PB-K, which, whilst allowing operation on normal overloads, will lock-in and prevent operation on large faults, leaving these to be dealt with by the large breaker. The relay so used follows the design of the type PB inverse time with definite minimum relay, but has an auxiliary device which operates to break the tripping circuit

when the current exceeds a predetermined value. The relay on the larger breaker has a longer time lag, but as the relay on the smaller breaker has been rendered inoperative, the large breaker is opened. As soon as this happens, the auxiliary device on the PB-K relay is reset, thus allowing the small breaker on the faulty feeder to trip. The faulty circuit now being cleared, the larger breaker can now be reclosed to resume normal service to healthy feeders.

Translay (*Metropolitan-Vickers Electrical Co., Ltd.*).

The difficulties associated with Balanced Voltage Protection led to new forms of feeder protection being evolved, of which the Translay is one.

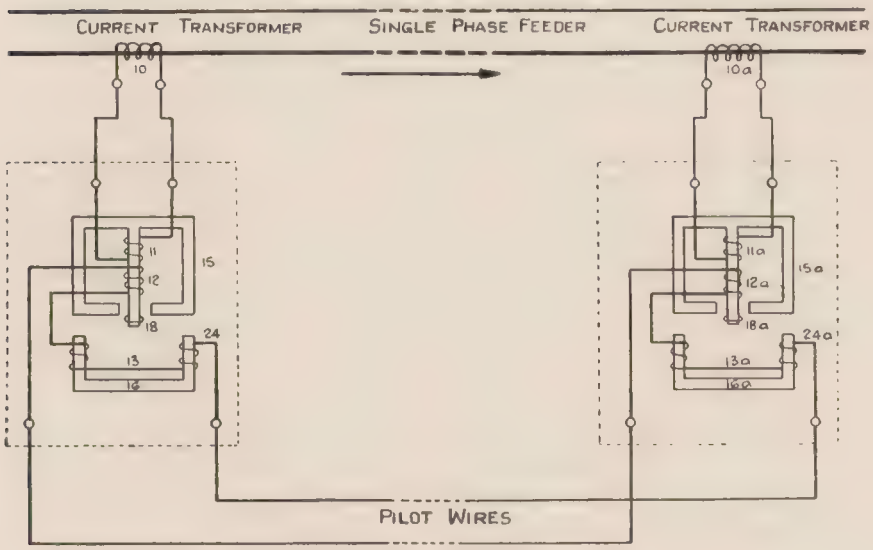


FIG. 20-43.—*Simplified diagram of Translay Feeder Protection* (*The Metropolitan-Vickers Elec. Co., Ltd.*).

As will be seen from the diagrams, it involves the use of pilot cables, but due to its design, suffers none of the disadvantages of earlier pilot schemes, is not affected by through faults (*i.e.*, is stable) and allows the use of ordinary current transformers.

The name Translay is evolved from the fact that the relay embodies a transformer feature. It provides complete protection against both earth and phase faults, can be applied to single or three-phase feeders, transformer feeders, feeders with a tee-off and parallel feeders. It is based on the established principle of the current entering at one end of a feeder being equal at any instant to that leaving at the other.

In its simplest form the operation of this system can be followed by reference to the simplified diagram, Fig. 20-43, for a single phase feeder, and noting that for the sake of clearness, tripping circuits have been omitted.

Under healthy conditions, current transformers 10 and 10a carry equal currents, and the coils 11 and 11a induce equal EMF's in the windings 12 and 12a. These latter windings are in opposition via the pilot wires with the operating windings 13 and 13a in series with them. Thus no forward torque is exerted on the disc. On the occurrence of a fault the current through one transformer is greater than the other, a small current circulates through the operating windings and pilots, and when it reaches the set value causes the relay to close the tripping circuit and disconnect the feeder.

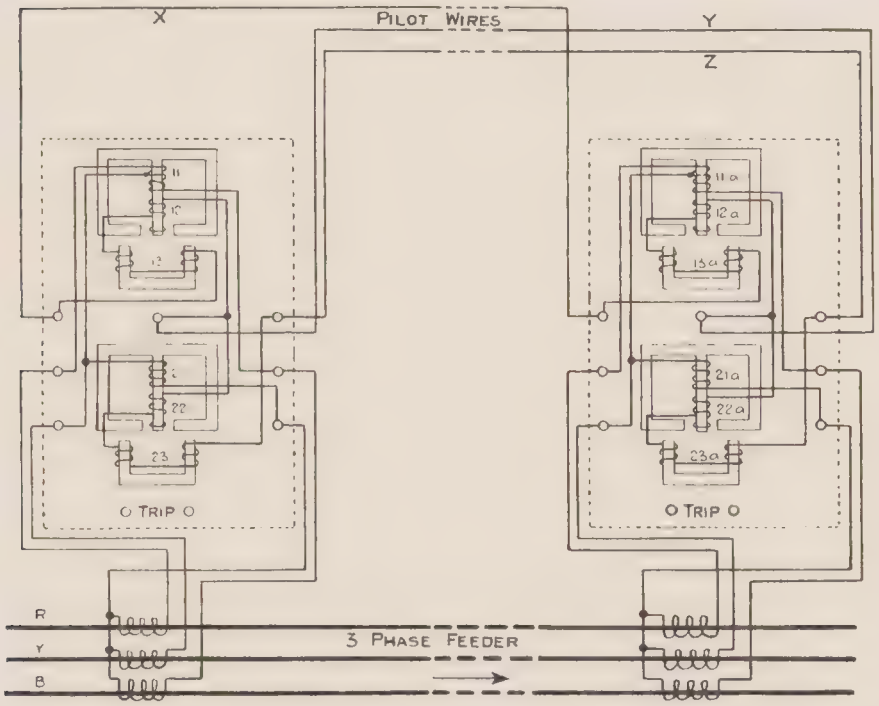


FIG. 20-44.—*Three-phase application of Translay Feeder Protection (The Metropolitan-Vickers Elec. Co., Ltd.).*

In the case of a three-phase feeder, a two-element relay is used at each end of the line, as shown. One element of this relay gives protection against phase faults and the other against earth faults, with independent settings.

The action under fault conditions is as follows:

On a phase fault between, say, phases R and Y, the current passes through the *upper* halves of coils 11 and 11a, and is greater in coil 11 than 11a, thus inducing an EMF in coil 12, which overcomes that in 12a. Current circulates through coils 13 and 13a and pilots X and Y. A small current will flow in coils 23 and 23a of the earth fault relay, but these will not operate because

there is no earth fault and the instantaneous values of current will be zero and no current will flow in coils 21 and 21a. Only the phase fault relay, therefore, will operate. A phase fault between phases Y and B causes operation by energising the *lower* halves of coils 11 and 11a, while a phase fault between R and B causes operation by energising the *whole* of coils 11 and 11a.

In the case of an earth fault on any phase, the instantaneous sum of the currents is not zero, and the resultant current flows through coil 21, which is connected on the core balance principle. There being no current in coil 21a, the E.M.F. induced in coil 22 will be unopposed and current will pass through operating coils 23 and 23a via pilots Y and Z, causing operation of the fault current relay.

This form of protection can be applied to transformer feeders (switched as one unit without intervening circuit breaker), to feeders with a tee-off (where the current entering is balanced against that leaving by two sources), and to parallel feeder protection (where a Translay element is combined with a directional element).

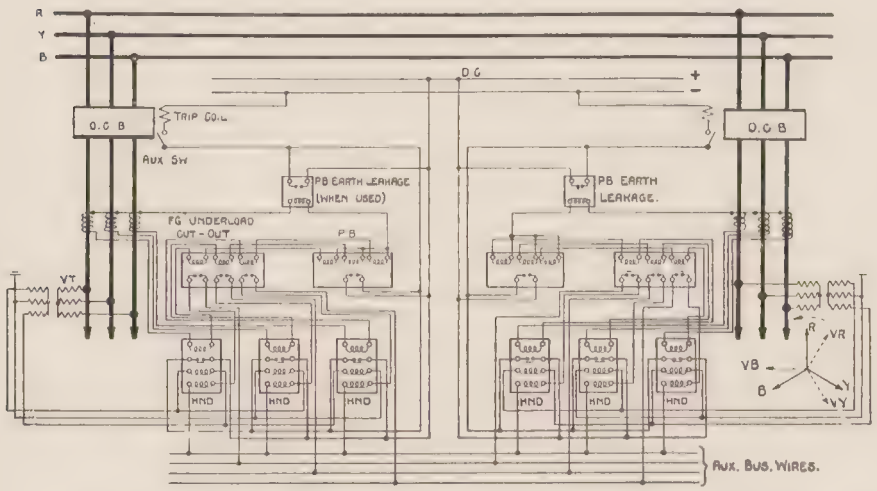


FIG. 20-45.—*Parallel Feeder Protection using HND relays (directional) and suitable for any number of feeders. Note back-up overcurrent protection and cut-out relays (The Metropolitan-Vickers Elec. Co., Ltd.).*

In the case of parallel feeder protection, any number of feeders can be so protected and future feeders brought into the scheme without alteration to existing connections.

Impedance (Distance) (M.V.E. Co. and others).

This form of protection needs no pilot cables, and is particularly suitable for use on long feeders.

In principle, the theory of this type is as follows:—

The impedance of a given feeder or section of a line has a constant value and therefore the relation between the fault current and the voltage existing

between any two points on a faulty line is known. The line impedance between the relay and the fault at any switching point depends on the distance between that point and the fault, and is measured by the ratio of the voltage on the line at the relay, to the fault current flowing.

In its simplest form an impedance relay has an operating force which is proportional to the fault current I and a restraining force proportional to the voltage E on the relay. The relay would then operate whenever the

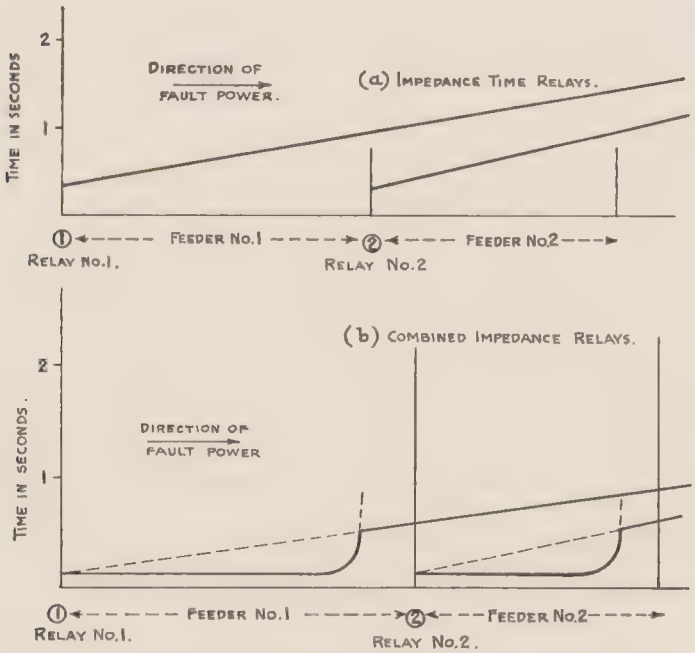
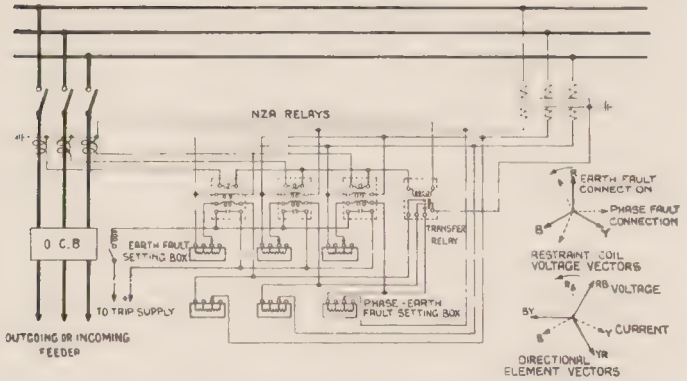


FIG. 20-46.—*Characteristic Curves for impedance relay:*
(a) Impedance-time relay;
(b) Combined Impedance relay
(The Metropolitan-Vickers Elec. Co., Ltd.).

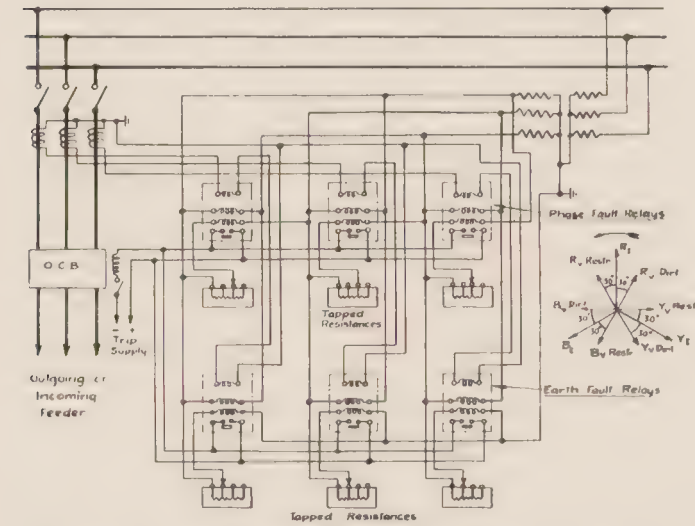
ratio E/I is less than a defined amount, *i.e.*, whenever the fault occurred within a given distance from the relay.

It is essential to use voltage transformers suitable for the scheme. Preferably three single phase units are recommended, but if a three-phase unit is used it must be of the " shell " type and not of the " core " type. The reason for this is that in the " core " type the two healthy limbs tend to maintain an appreciable flux in the limb short-circuited by a line fault to earth. The resulting voltage from the secondary of the shorted limb prevents the correct reproduction of line voltage conditions on the relay (see Chapter XIX).



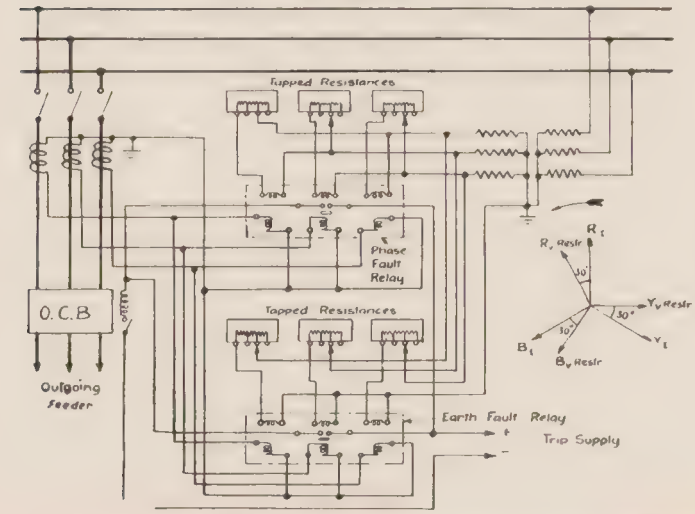
(a)

Scheme of Directional Earth-fault and Phase fault Impedance Protection using transfer relay and one set of Impedance relays.



(b)

Scheme using separate sets of relays for Earth-faults and Phase faults, omitting transfer relay.



(c)

Scheme of non-directional Earth and Phase fault protection, using separate relays and omitting transfer relay.

FIG. 20-47.—*Diagrams showing connections for Impedance Protection (The Metropolitan-Vickers Elec. Co., Ltd.).*

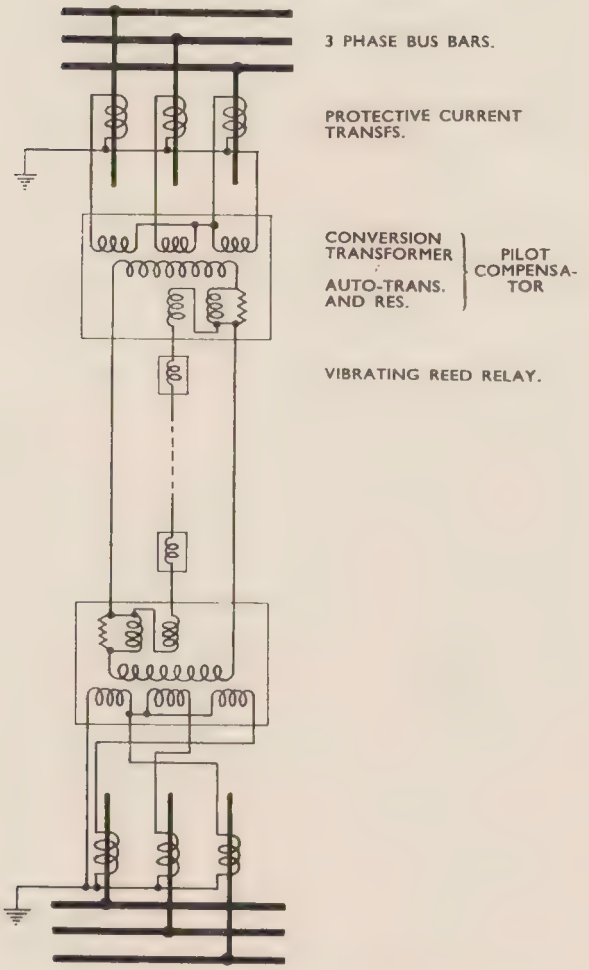


FIG. 20-48. *Self-Compensating Feeder Protection —Schematic Diagram (The British Thomson-Houston Co., Ltd.).*

Self-Compensating (B.T.H. Co.).

This is another scheme involving the use of pilots and is designed to overcome the difficulties and disadvantages of the balanced voltage scheme. It requires current transformers to give correct ratio up to the full through short-circuit capacity of the system, but not the pairing and balancing of such transformers.

From the schematic diagram, it will be seen that in addition to the current transformers at each end of the line, there is also used a pilot compensator, and a vibrating reed relay. The compensator comprises a

conversion transformer, a resistance and an auto-transformer. The conversion transformer, comprising primary and secondary windings is so connected that a three-phase primary current induces a single-phase current in the secondary, and is more sensitive to earth faults than to phase faults. The resistance is adjustable to suit the length of pilot cable, while the auto-transformer has a ratio such that in conjunction with the resistance, capacity currents in the pilots are eliminated.

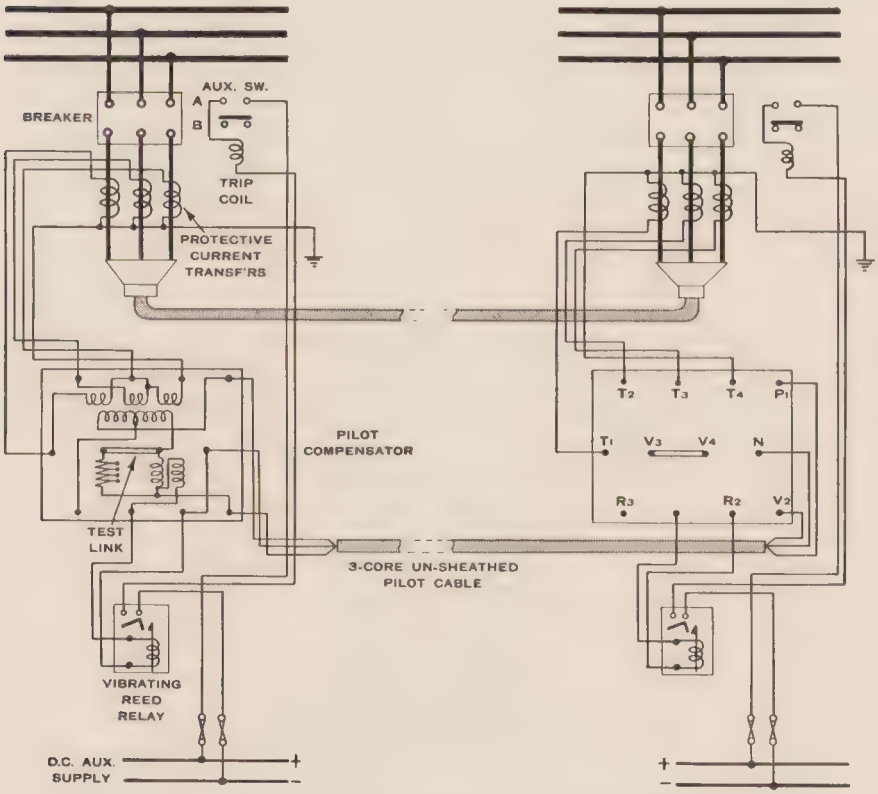


FIG. 20-49.—*Self-Compensating Feeder Protection as applied to a three-phase Feeder (The British Thomson-Houston Co., Ltd.).*

The vibrating reed relay operates on the resonance principle and remains undisturbed by any current other than that at normal system frequency. Thus transient currents induced in the circuit due to high frequency disturbances will not cause false operation.

The principle of operation briefly is as follows:—

The single phase current induced in the secondary of the conversion transformer at one end, circulates via two outer pilot wires with the single phase current similarly induced at the other end. The relays are connected one at each end of the centre pilot wire between equipotential points.

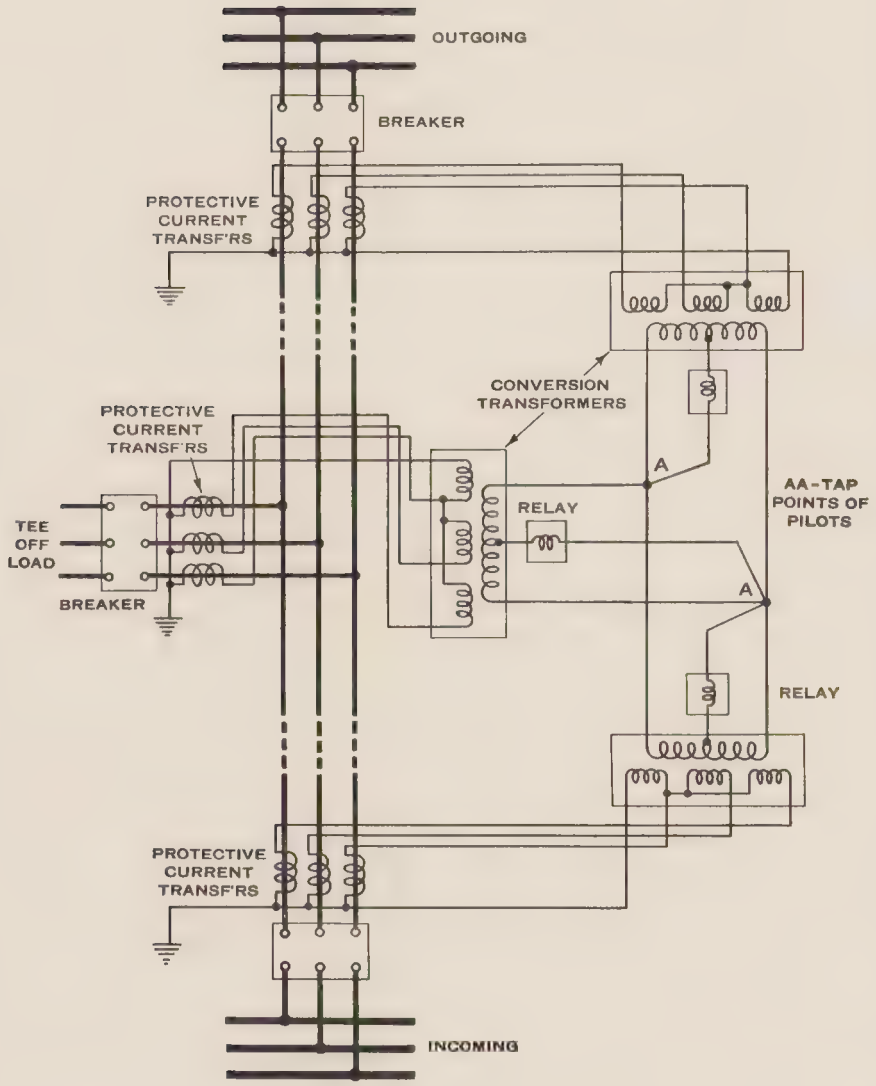


FIG. 20-50.—*As Fig. 20-49, but with a tee-off (The British Thomson-Houston Co., Ltd.).*

Under healthy conditions, *i.e.*, with currents of equal magnitude flowing into and out of the feeder, no current will flow in the centre pilot and the relays will not be energised. When a fault occurs on the protected section, the inequality of currents in and out is upset, thus disturbing the balance in the outer pilots and causing a current proportional to the difference between incoming and outgoing primary currents to flow in the centre pilot. On reaching the predetermined value, the relays operate to trip the circuit breakers.

This form of protection can be applied to a feeder with a tee-off in the manner shown.

Split Pilot (Messrs. A. Reyrolle & Co., Ltd.).

A pilot system again designed to overcome the difficulties of the balanced voltage system. For systems up to about 44 kV the current transformers used are of the distributed air gap type. Above this voltage the difficulties experienced in accommodating DAG transformers in circuit breaker bushings, render the use of solid-core transformers desirable and in such a case, a DAG summation transformer is used. The two diagrams produced illustrate the difference.

It should be noted that in the schemes using DAG current transformers, those at the two ends on one phase have the same winding ratio, but those in different phases have different winding ratios. In the scheme using a DAG summation transformer, the line current transformers are similar.

Under healthy conditions the current due to the two sets of current transformers in series divides equally between the two parts of the split pilot, and therefore equal currents flow through the two windings of the differentially wound split-pilot transformers, neutralising each other so that no current flows in the relay circuit. The system is stable, so that this holds good no matter what value of current circulates in the pilot system and is thus proof against unwanted tripping due to through faults.

The means provided for tripping on the occurrence of a fault within the protected zone is that of the mid-point tripping connection, made as a plain cross-connection between a common pilot and one core only of the split pilot. This connection is made at middle and equipotential points.

On an internal fault occurring, one set of current transformers such as at " A," will carry a greater current than those at " B," and generate a greater secondary current. This additional current will be imposed on a still balanced circuit, and will circulate along the left-hand half of the common pilot, across the mid-point connection to the middle point of the split-core to which it is connected. From this point the additional current flows back to the left-hand junction of the split-pilot by two parallel paths—one, the short path represented by the left-hand end of split pilot 3, and the other a long path represented by the right-hand end of split pilot 3, and the whole length of split pilot 2. The ratio of these lengths is clearly 1 : 3 and three-quarters of the additional (tripping) current flows in the short path and one quarter in the long path.

In the differential windings of the split-pilot transformer at end " A " one winding carries three-quarters of the tripping current and the other one-quarter, both currents being in the same direction, giving a combined effect equal to one-half the tripping current. In the split-pilot transformer at end " B " each winding carries one-quarter of the tripping current, but in opposite directions, the combined effect being equal to one-half.

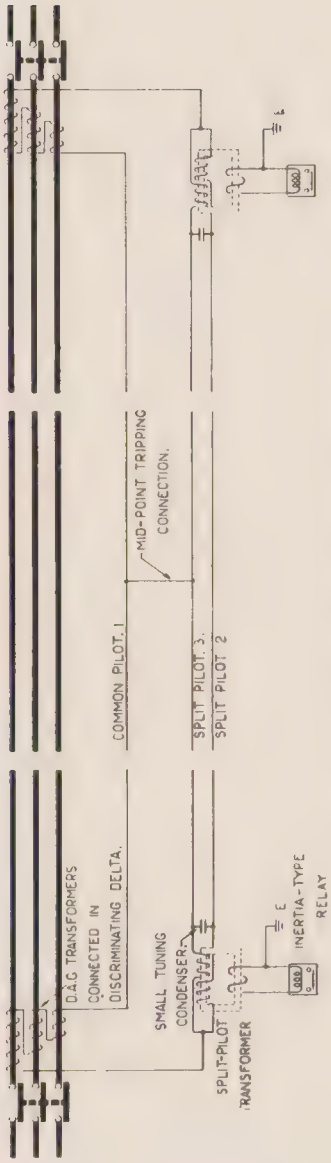


FIG. 20-51.—*Split Pilot Feeder Protection (A. Reyrolle & Co., Ltd.).*

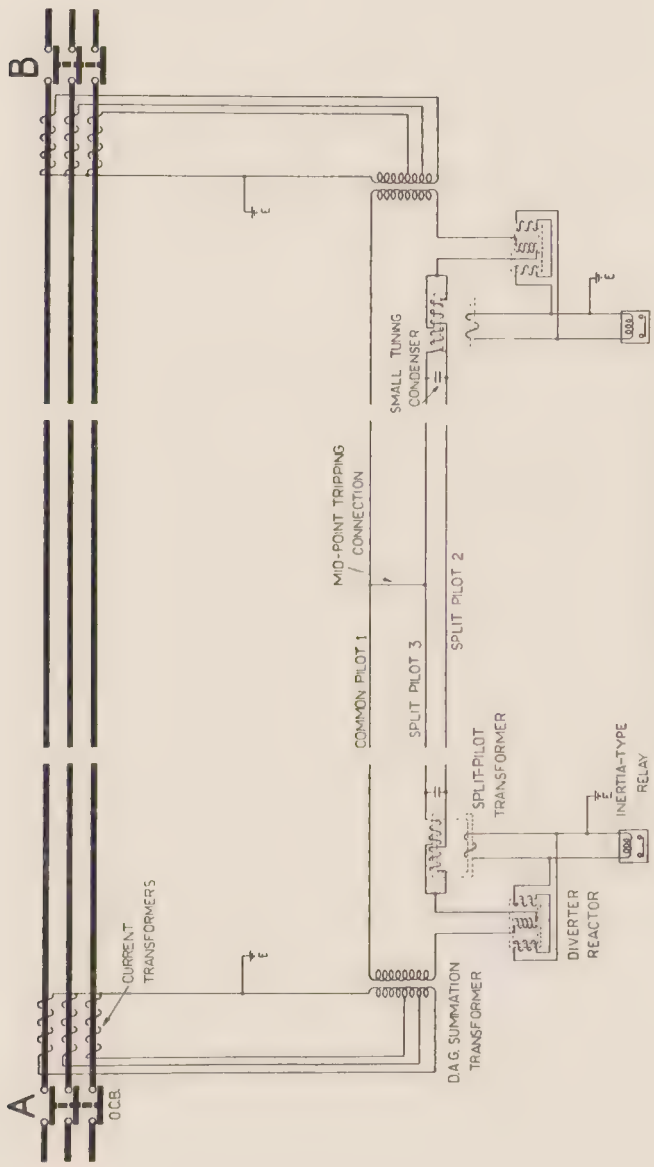


FIG. 20-52.—*Split Pilot Feeder Protection (A. Reyrolle & Co., Ltd.).*

Thus, the difference current due to a fault is divided to provide equal tripping energy at each end. In the case where a DAG summation transformer is used, it is necessary to include a divertor reactor, the purpose of which is to compensate for the unbalance due to the use of solid-core current transformers.

As in previous cases, this system can be used to protect feeders with a tee-off.

Solkor Protection.

This scheme (due to Messrs. A. Reyrolle & Co., Ltd.) derives its name from the fact that ordinary solid-core current transformers can be used, these being of standard 15 VA Class C or even lower rating. It is a pilot scheme (two pilots 7/·029 or of smaller section are required), which operates on the Merz-Price Balanced Voltage principle. The three current transformers at each end of the line to be protected are connected, as shown in the diagram, to a solid-core summation transformer. The single-pole relay has its operating coil energised from the secondary winding of a relay transformer, whose primary winding is in series with the pilot wires. The

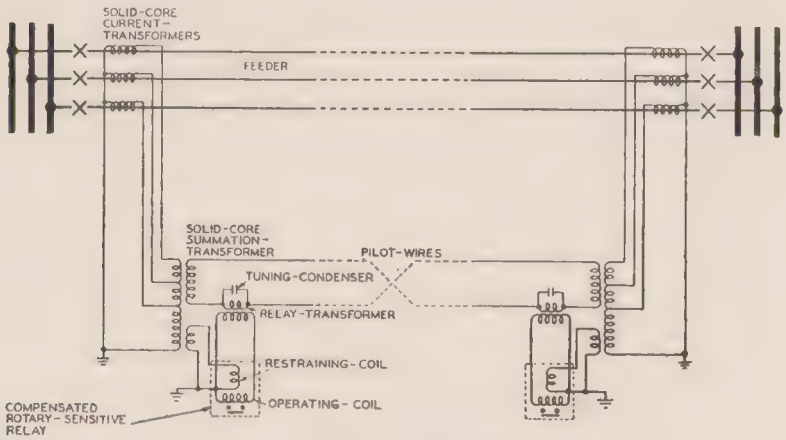


FIG. 20-53.—*" Solkor " Feeder Protection (A. Reyrolle & Co., Ltd.).*

restraining coil of the relay is connected to a tertiary winding on the solid-core summation transformer. It will be noted that the operating-coil circuit is tuned so that the relay only responds to currents at or near to fundamental system frequency. The scheme is sensitive both to earth and phase faults, with greater sensitivity in the case of the former.

BIBLIOGRAPHY.

Protective Gear Handbook, M. Kaufman (Pitman and Sons).

Automatic Protection of A.C. Circuits, G. W. Stubbings (Chapman and Hall).

"THE MANAGEMENT OF PROTECTIVE GEAR SYSTEMS ON POWER SUPPLY SYSTEMS," W. Casson and F. H. Birch, "Journal I.E.E.," Part II, Vol. 1942.

"BUSBAR ZONE PROTECTION," T. W. Ross, "Metropolitan-Vickers Gazette," 1936, Vol. XVI, p. 266.

"RECENT DEVELOPMENTS IN THE PROTECTION OF THREE-PHASE TRANSMISSION LINES AND FEEDERS," T. W. Ross and H. C. Ball, "Journal I.E.E.," 1930, Vol. 68, p. 704.

"THE PROTECTION OF PARALLEL FEEDERS, INTERCONNECTORS AND TRANSFORMERS," W. Wilson, "World Power," 1930, Vol. 15, p. 371.

"APPLICATIONS AND LIMITATIONS OF INVERSE-TIME OVERLOAD RELAYS TO THE PROTECTION OF AN 11kV NETWORK," J. W. Gallop and R. H. Bousfield, "Journal I.E.E.," 1940, Vol. 87, p. 113.

"MAINTENANCE OF RELAYS AND ASSOCIATED EQUIPMENT," J. R. Brookman, "Journal I.E.E.," 1940, Vol. 87, p. 485.

"SAFEGUARDS AGAINST INTERRUPTION OF SUPPLY," H. W. Clothier, B. H. Leeson and H. Leyburn, "Journal I.E.E.," Vol. 82, No. 497, May, 1938.

"BUSBAR PROTECTION: A CRITICAL REVIEW OF METHODS AND PRACTICE," M. Kaufman and W. Szwander, "Journal I.E.E.," Vol. 90, Part II, No. 17, October, 1942.

NOTE.—In the books by Kaufman and Stubbings, useful chapters appear dealing with the testing and maintenance of protective systems which repay study.

CHAPTER XXI

APPLICATION OF INDUCTION RELAYS*

CHAPTER XX is devoted to descriptions of various relay systems available for the protection of a.c. power networks. Here we are concerned with certain practical details of the application of the ordinary induction relay having an inverse time and definite minimum characteristic, as shown by Fig. 21-1.

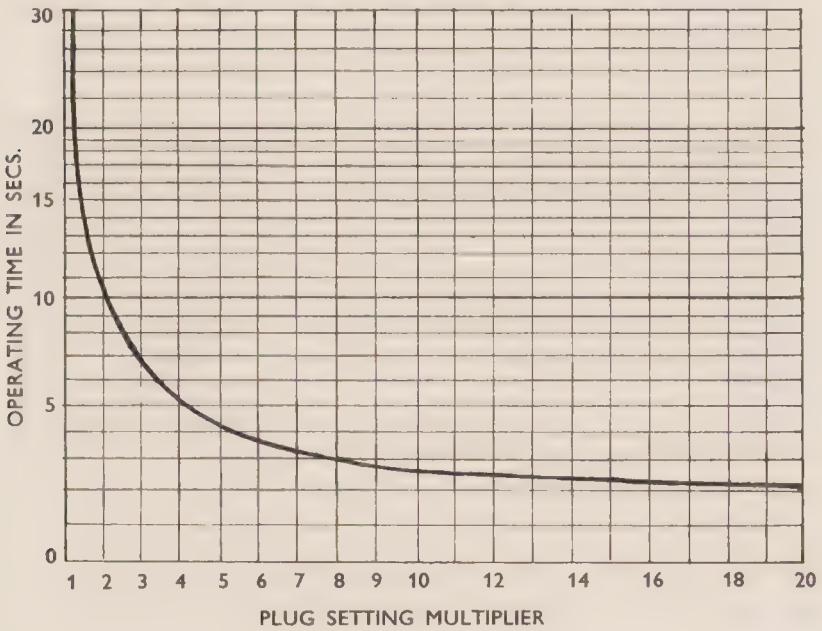


FIG. 21-1.

Where unit systems of protection are used for generators, transformers or feeders, induction relays are used as standby or back-up protection. With secondary or medium power networks, as largely encountered in the industrial field, induction relays are used to a considerable extent as the main feeder protection.

There are at least six firms in this country making induction relays and apart from some minor variation in the terms used to describe the settings, there are no fundamental differences arising in the matter of application.

* *Contributed by W. A. Brown, A.M.I.E.E., A.M.I.Mech.E., late of J. & P. Switchgear Technical Engineering Department, and now Engineer to Northmet No. 2 Sub-Area, Eastern Electricity Board.*

The induction relay has two sets of adjustments and these refer to time and current.

Current Setting.

The range of current settings is usually expressed as a percentage of the full load secondary current of the associated current transformer(s).

A common range for phase fault relays is 50/200% of 5, 1 or 0·5 amperes as the case may be. There are seven steps each differing by 25%. Similarly, the range for earth fault relays is 10/70% in steps of 10%. The current setting is sometimes referred to as " the plug setting," and multiples of this value form the base of the characteristic curve.

The first timing given by the characteristic curve corresponds to 1·3 times the current setting, and in the case of Fig. 21-1 this is 30 seconds. At current values lying between the current setting and 130% the relay disc may commence to rotate but the operating time would be uncertain.

Time Setting.

The operating time forms the vertical scale of the characteristic curve It is seen that as the current increases (given in terms of current setting multiplier by the characteristic curve) the operating time decreases until it becomes sensibly constant. This latter value is known as the definite minimum or saturation time. The maximum value of the saturation time is used to define the time range of the relay, so that Fig. 21-1 refers to a 0/2 seconds relay, this probably being the most common range in use. The majority of relays have their saturation time range graduated in fractions of a second. Certain makes, however, have the saturation time range simply graduated from 0 to 1 and the values are known as time multiplier settings or constants.

Strictly speaking the range shown by Fig. 21-1 is 0/2·2 seconds so that in this case a time multiplier of 1 would correspond to 2·2 seconds and similarly that of 0·5 would correspond to 2·2 seconds $\times$ 0·5 equals 1·1 seconds and so on. As it is probably a little clearer we will refer to saturation times in seconds. The characteristic curve engraved upon each relay dial plate (similar to Fig. 21-1) shows the maximum operating times that can be obtained. Shorter operating times may be used by setting the saturation time at a lower value. The actual operating time for the selected saturation time setting is obtained by taking the time from the maximum curve at any desired point and multiplying by the ratio of the saturation time setting to the maximum saturation time.

This process of obtaining any desired intermediate operating time is due to the proportionality of the characteristic curve, i.e. : –

$$\frac{\text{Saturation time setting}}{\text{maximum saturation time}} = \frac{\text{Operating time}}{\text{maximum operating time}} \qquad \text{(i)}$$

In other words a series of curves can be obtained each corresponding to any selected saturation time.

Example 1.

Referring to Fig. 21-1 at current setting multiplier of 8 the maximum curves gives an operating time of 3·0 seconds corresponding to a saturation time of 2·2 seconds.

Determine operating time at same current setting multiplier with saturation time of 1·1 seconds :—

from (i)

$$\text{Operating time} = \text{Maximum operating time} \times \frac{\text{Saturation time setting}}{\text{maximum saturation time}} \quad \text{(ii)}$$

$$= 3{\cdot}0 \times \frac{1.1}{2{\cdot}2} = 1{\cdot}50 \text{ seconds.}$$

EXAMPLE 2.

Feeder with normal loading 280 amperes.

Current transformer ratio 300/5.

Overcurrent relay settings 50/200%, 0/2 seconds.

Assume relay current setting 100% and saturation time 2·2 seconds.

Determine operating current at 30 seconds :—

100% current setting = 5 amperes in relay

5 amperes × 1·3 factor = 6·5 amperes in relay

Primary current = current transformer ratio × relay current

$$= \frac{300}{5} \times 6{\cdot}5 = 390 \text{ amperes.}$$

EXAMPLE 3.

Feeder with same conditions as Example 2.

The maximum fault current is given as 4,500 amperes.

Determine operating time under this condition :—

Current setting = 100% = 300 amperes

$$\therefore \quad \text{Current setting multiplier} = \frac{4{,}500}{300} = 15$$

Reading from the characteristic curve Fig. 21-1 the operating time is 2·30 seconds.

(With a saturation time of 1·1 seconds this operating time would be reduced to 1·15 seconds.)

GRADING METHODS.

There are three methods of grading induction relays to obtain selective operation :—

(1) By grading with reference to saturation times only. This may be called time grading.

(2) By varying current settings and working with a constant saturation time. This may be called current grading.

(3) By selecting combinations of saturation times and current settings to give the shortest possible operating times. This may be called time/current grading.

Obviously the third method is the best as short operating times are desirable in any network and are essential where the fault capacity is high.

TIME GRADING.

The saturation times are selected so that a difference of say 0·5 second obtains between each relay in series. This is justified where the fault

currents are sufficient to cause all the relays to operate at their saturation times. Otherwise, it will be found that unduly long operating times may result near the source of supply.

Alternatively this aspect is somewhat overcome by using relays having a steeper characteristic curve reaching the saturation time at lower current setting multipliers as shown by Fig. 21-2.

Current Grading.

Although it is possible to grade two or three relays in series with constant saturation time settings by varying the current settings so that

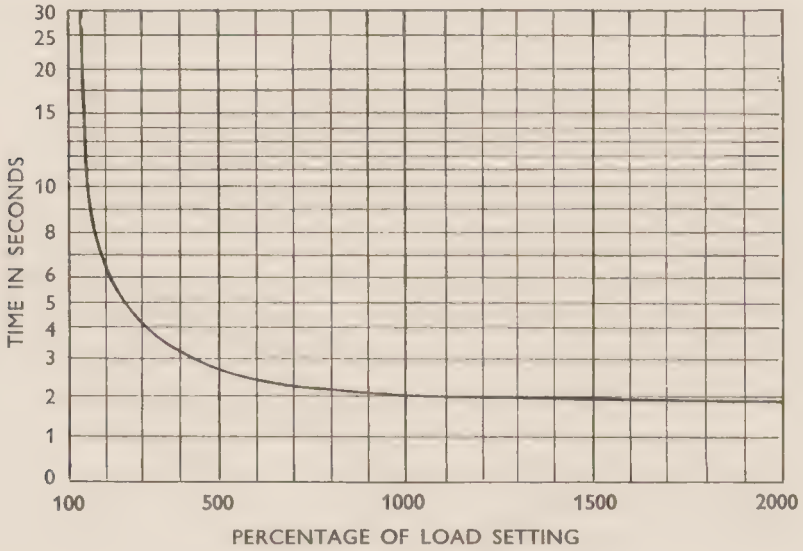


Fig. 21-2.

the inverse part of the curve is used to obtain the grading interval, the method has little practical use. A necessary condition, as implied above, is that the fault currents must not cause the relays to operate at their saturation times.

Current grading occurs, however, in the case of parallel circuits, such as those including power transformers, where the division of the primary fault current is used to obtain selective operation by using the inverse part of the characteristic.

Current/time Grading.

By consideration of the fault currents obtained in the network it is usually possible to select the saturation time and current settings so that the relay operating times vary with reference to the position of the fault.

The relay at the furthest point of the network is given the lowest permissible current setting and saturation time.

The operating time at the maximum fault current, plus the grading interval, becomes the operating time of the next relay when backing up the first relay. By using a higher current setting, this operating time is selected so that the relay works towards the inverse part of the curve and so permits the use of a shorter saturation time. Consequently, when a fault occurs adjacent to the second relay the higher fault current will increase the current setting multiplier and cause the relay to operate, in this instance, at or very near its saturation time. The next relay is set in a like manner to back up the second relay and so on. Examination will show that the higher the current setting the shorter will be the operating time of the relay for a fault at the beginning of its own section. Also the current settings expressed in primary current, of each relay, working back to the source should be at least equal to, if not higher than, the preceding relays to ensure selectivity over the whole of the operating range.

Operating Time Intervals.

General practice is to allow an interval of 0·5 second between adjacent relays providing these are working at or near saturation times, i.e., on the more or less flat part of the curve. When grading upon the more inverse part of the curve it may be thought reasonable to allow a slightly longer interval. The relay percentage error may not increase to any great extent but the absolute value in time would be greater. Consequently an additional margin of say 10% of the operating time may be advisable where the latter exceeds twice the saturation time. Where, however, the relay settings are based upon the instantaneous symmetrical (R.M.S.) fault current, the decrement of the circuit may be sufficient to make this precaution unnecessary. This is due to the shape of the characteristic curve automatically providing wider separation between relays as the operating time increases by reason of the decaying fault current.

The question as to whether the time interval of 0·5 second can be reduced in any particular case depends upon consideration of the following points :—

(1) Clearance time of circuit-breakers under various fault conditions.
(2) Relay timing errors.
(3) Current transformer errors.
(4) Accuracy of data used for fault calculations.
(5) Margin for stability.

With modern circuit-breakers, improvements have been made with regard to (1) although general acceptance of a shorter time interval has not so far come about. The tendency appears to be to use the larger margin to make stability of operation more definite. Improvements have also been made in relay design largely to give good proportionality of the characteristic and also to avoid overswing, i.e., the problem of arresting movement of the disc after the fault current is interrupted.

Current transformer errors usually cause more concern at the higher values of fault current and are largely due to the effect of saturation. In addition, therefore, to the falling off in ratio which in itself may be sufficient to prevent operation at the saturation time intended, the wave form of the secondary current becomes distorted and this again causes the operating

time to be longer. Obviously, the use of well designed current transformers having a liberal core section will assist in accurate grading.

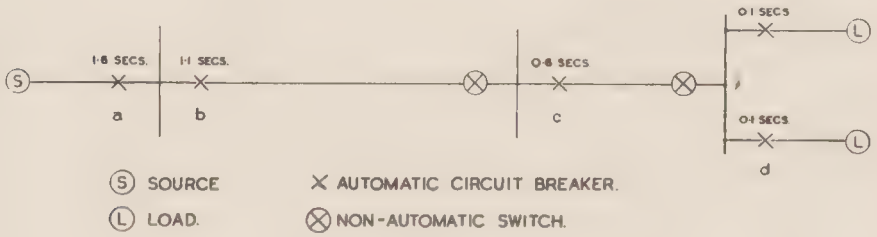


FIG. 21-3.

In regard to (4) the calculated values of fault current will generally be on the high side even when all the factors such as correct machine, transformer and feeder data are taken into account.

It will also be appreciated that to use short time intervals with consistently correct operation requires first class maintenance of the switchgear and relays. Slight variations in performance due to ordinary service conditions and practical errors in setting the time scale pointer are covered by the stability margin (5).

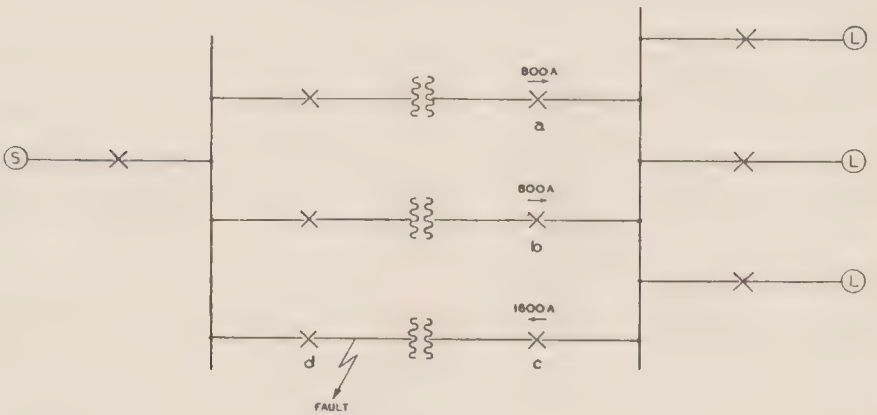


FIG. 21-4.

EXAMPLE 4.

Fig. 21-3 shows a series network in which the relays at (a), (b), (c), (d), have their saturation time settings selected by time grading. It can be seen that the relay furthest from the source (d) has the shortest operating time of 0·1 second, and the remainder increase by 0·5 second in each case towards the power source.

EXAMPLE 5.

Fig. 21-4 shows three power transformers in parallel with a fault in one of the circuits as indicated.

At the inception of the fault practically all the current would be fed through (d) so that the relay at this point would trip its associated circuit-breaker. Thereafter the fault current would be fed through the two healthy circuits as shown.

Taking current transformer ratio in each case as 200/5 amperes and relay current setting of 150% with saturation time of 1·1 second we get :—

Relays (a) and (b)

Current setting = 150% = 300 amperes

$$\therefore \text{ Current setting multiplier } = \frac{800}{300} = 2{\cdot}66$$

from maximum time curve Fig. 21-1 operating time is eight seconds so that at saturation time of 1·1 the operating time is four seconds.

Relay (c)

$$\text{Current setting multiplier } = \frac{1{,}600}{300} = 5{\cdot}33$$

and operating time at saturation time of 1·1 second is two seconds.

This leaves a margin of two seconds which should be sufficient to ensure selective operation.

RELAY POINT	C.T. RATIO.	FAULT AMPS	LOAD AMPS
a.	400/5.	6,000	380
b.	400/5.	6,000.	320.
c.	200/5.	4,000	180.
d.	100/5.	2,800.	70.

FIG. 21-5.

EXAMPLE 6.

A simple series network is shown by Fig. 21-5 ; the current transformer ratios and current expected for faults adjacent to each relay point are also indicated.

In practice it is usual to follow a middle course in selecting the current setting since conditions may arise to limit the fault current to lower values.

The current settings and operating times are determined as follows :—

(1) Current setting of relay (d) can be fixed at 100%. The saturation time can be the minimum permissible, i.e., 0·1 second.

Current setting = 100% = 100 amperes

$$\therefore \text{ Current setting multiplier } = \frac{2{,}800}{100} = 28$$

The relay will operate at its saturation time.

(2) It follows that the operating time of relay (c), to obtain selectivity with (d), must be at least 0·5 + 0.1, i.e., 0·6 second.

Consider current setting of (c), 175%

Current setting = 175% = 350 amperes

$$\therefore \text{ Current setting multiplier } = \frac{2{,}800}{350} = 8$$

Operating time from maximum curve is 3·0 seconds.

Rearranging (i) we get

$$\text{Saturation time setting} = \text{operating time} \times \frac{\text{Maximum saturation time}}{\text{Maximum operating time}} \qquad \text{(iii)}$$

$$= 0{\cdot}6 \times \frac{2{\cdot}2}{3{\cdot}0} = 0{\cdot}44 \text{ seconds.}$$

Now find operating time of relay (c) with fault close to this relaying point :—

$$\text{Current setting multiplier} = \frac{4{,}000}{350} = 11{\cdot}4$$

from maximum curve operating time is 2·6 seconds.

Using (ii)

$$\text{Operating time} = 2{\cdot}6 \times \frac{0{\cdot}44}{2{\cdot}2} = 0{\cdot}52 \text{ seconds.}$$

(3) The operating time of relay (b) must be at least 0·5 + 0·52, i.e., 1·02 seconds.

Consider current setting 150%

$$\text{Current setting multiplier} = \frac{4{,}000}{600} = 6{\cdot}66$$

and operating time from maximum curve is 3·4 seconds.

$$\text{Saturation time setting} = \frac{1{\cdot}02}{3{\cdot}4} \times 2{\cdot}2 = 0{\cdot}66 \text{ second.}$$

operating time of relay (b) with fault close thereto

$$\text{Current setting multiplier} = \frac{6{,}000}{600} = 10$$

and operating time from maximum curve is 2·7 seconds.

$$\text{Operating time} = 2{\cdot}7 \times \frac{0{\cdot}66}{2{\cdot}2} = 0{\cdot}81 \text{ seconds.}$$

(4) The operating time of relay (a) to grade correctly with relay (b) must be equal to at least

0·81 + 0·5, i.e., 1·31 seconds

Consider current setting of 200%

$$\text{Current setting multiplier} = \frac{6{,}000}{800} = 7{\cdot}5$$

and time from maximum curve is 3·2 seconds.

$$\text{Saturation time setting} = \frac{1{\cdot}31}{3{\cdot}2} \times 2{\cdot}2 = 0{\cdot}897$$

say 0·9 seconds.

Summarising the above :—

TABLE I

Relay	Current Setting	Saturation Time Setting Seconds	Operating Time Seconds
a	200	0·9	1·31
b	150	0·66	0·81
c	175	0·44	0·52
d	100	0·10	0·10

As a matter of comparison it is assumed that the fault conditions of Fig. 21-5 also apply to Fig. 21-3 ; the operating times calculated from the original saturation time settings assuming similar current settings would be as follows :—

TABLE II

Relay	Fault Current Amperes	Current Setting %	Current Setting Multiplier	Saturation Time Setting Seconds	Operating Time Seconds
a	6,000	200	7·5	1·6	2·26
b	6,000	150	10	1·1	1·35
c	4,000	175	11·4	0·6	0·71
d	2,800	100	28	0·1	0·10

It can be seen that the operating times are very much longer, in fact there is nearly one second difference at the source.

With the time grading method the current settings are generally constant, so that a further comparison is given below :—

TABLE III

Relay	Fault Current Amperes	Current Setting %	Current Setting Multiplier	Saturation Time Setting Seconds	Operating Time Seconds
a	6,000	150	10	1·6	1·96
b	6,000	150	10	1·1	1·35
c	4,000	150	13·3	0·6	·65
d	2,800	150	18·7	0·1	·10

It is seen that the first method, i.e., current/time grading, still gives much shorter operating times.

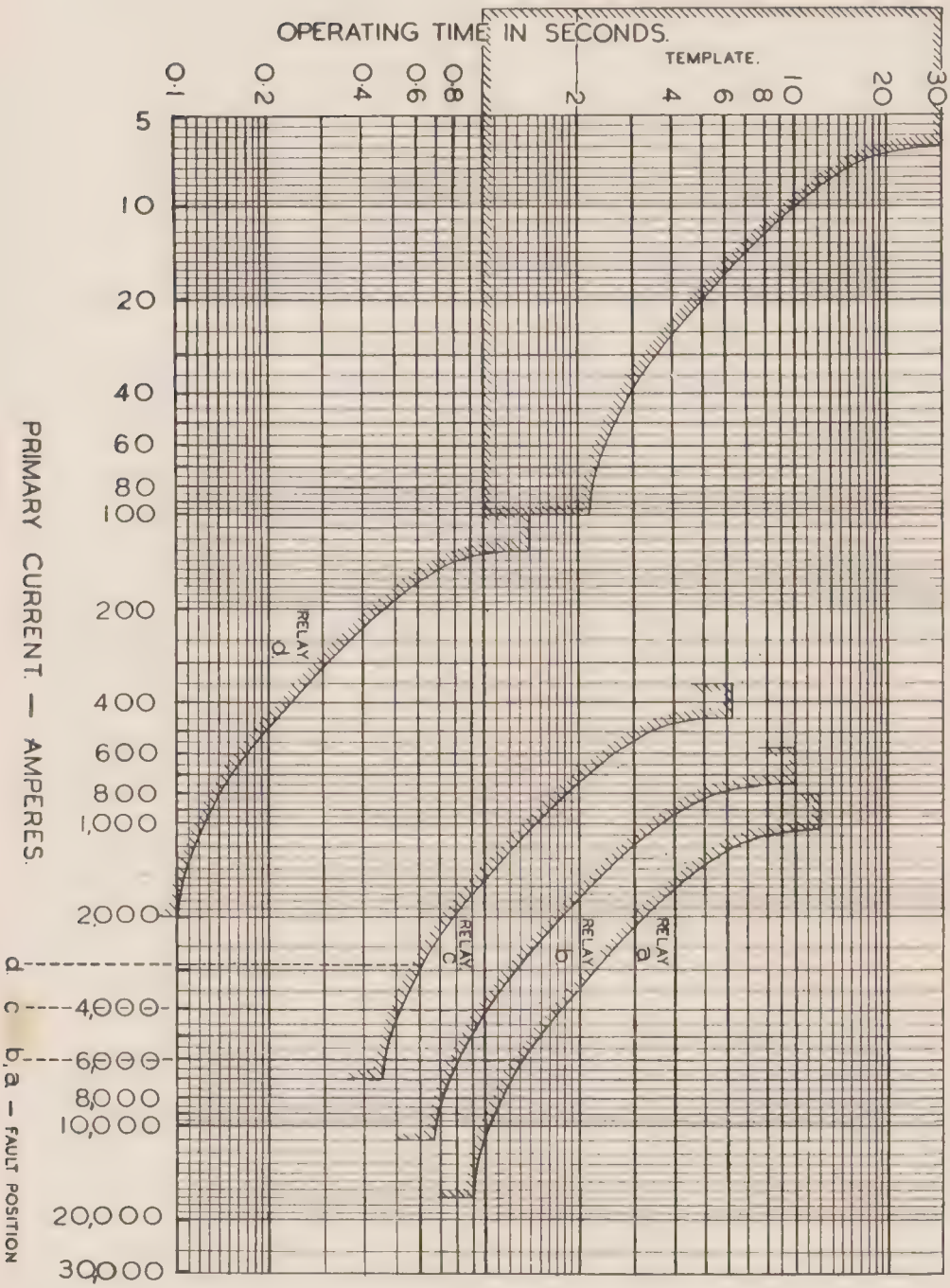


FIG. 21-6.—*Chart for determining Time Settings.*

EXAMPLE 7.

Taking the network shown by Fig. 21-5 the time settings will be checked by a graphical method. A chart is made up as Fig. 21-6 noting that logarithmic scales are used. The maximum curve is drawn out by reference, in this instance, to the 100/5 c.t. ratio and 100% current setting; the current setting multiplier is expressed in primary current, i.e. current setting multiplier of 20 corresponds to 2,000 amperes. A template is then made of cardboard or better still of celluloid. Moving the template vertically changes the saturation time setting and moving it horizontally alters the current setting. Ordinates are drawn corresponding to the fault currents at each relay section.

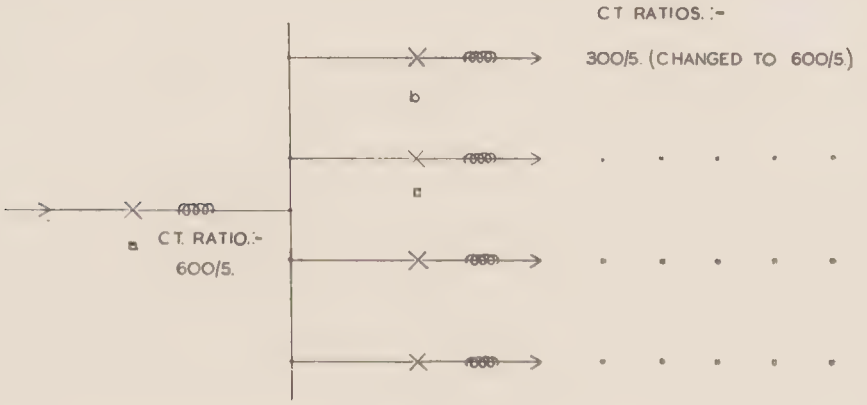


FIG. 21-7.

Using the saturation time settings obtained by example 6, Table I. the curves corresponding to relays (a), (b), (c) and (d) are marked on the chart by means of the template as shown. This demonstrates the time intervals between adjacent relays.

Now, taking another viewpoint it can be seen that the template could be used to determine the settings without the time/current calculations of example 6. The method is frequently used in practice and is regarded as indispensable (apart from the tedious plotting of numerous curves) where relays having different characteristic curves are used.

EXAMPLE 8.

An 11 kV bulk supply is brought into a switching station as shown by Fig. 21-7, the supply authorities switchgear equipment includes current transformers of ratio 600/5 amperes with 0/2 seconds relay (curve as Fig. 21-1) having current setting 150% and saturation time setting 1·40 seconds. The maximum and minimum three-phase fault capacity has been given by the supply authority as 175 MVA and 120 MVA respectively.

In this example the consumer's relays (b) and (c) will be set to give the maximum operating time, consistent with grading correctly with relay (a), so as to allow for the reasonable grading of other relays in the consumers network.

Relay (a)

$$\text{Maximum fault current} = \frac{175{,}000}{11 \times 1{\cdot}73} = 9{,}200 \text{ amperes}$$

$$\text{Current setting} = 150\% = 900 \text{ amperes}$$

$$\therefore \text{ Current setting multiplier} = \frac{9{,}200}{900} = 10{\cdot}2$$

operating time from maximum curve 2·7 seconds.

With saturation time of 1·4 seconds

$$\text{Operating time} = \frac{1{\cdot}4}{2{\cdot}2} \times 2{\cdot}7 = 1{\cdot}72 \text{ seconds.}$$

Relays (b) and (c) (300/5)

Operating time will be at least 1·72 — 0·5 = 1·22 seconds

Try current setting 150% = 450 amps

$$\therefore \text{ Current setting multiplier} = \frac{9{,}200}{450} = 20{\cdot}4$$

The relays will, therefore, operate at or near the saturation time setting of 1·22 seconds.

Now assume that 600/5 instead of 300/5 amperes C.T. ratio is used for (b) and (c). This reduces the current setting multiplier to 10·2 as for relay (a) and with operating time of 2·70 seconds from the maximum curve a saturation setting of 1·00 second would be necessary to obtain an operating time of 1·22 seconds.

Now assume that at the next relay point in the consumer's network that the fault capacity is reduced to 90 MVA.

We get for relays (b) or (c)

$$\text{Fault current} = \frac{90{,}000}{11 \times 1{\cdot}73} = 4{,}730 \text{ amperes}$$

(1) With current transformer ratio 600/5 amperes and current setting 150%

$$\text{Current setting multiplier} = \frac{4{,}730}{900} = 5.25$$

so that with saturation time setting of 1·0 second the operating time becomes :—

$$4 \times \frac{1{\cdot}0}{2{\cdot}2} = 1{\cdot}82 \text{ seconds}$$

(2) With current transformer ratio 300/5 amperes and current setting 150%

Current setting multiplier is 10·5.

With saturation time setting of 1·22 seconds the operating time becomes 1·47 seconds.

Arrangement (1) gives more time for further grading than (2) although a shorter saturation time is used. This demonstrates why in certain cases it is necessary to choose the current transformer ratio to give a suitable current setting multiplier, rather than to work upon the normal loading of the feeder.

Check operation of relays (b) and (c) at lower fault capacity.

$$\text{Fault current} = \frac{120{,}000}{11 \times 1{\cdot}73} = 6{,}300 \text{ amperes}$$

$$\text{Current setting multiplier} = \frac{6{,}300}{900} = 7$$

and corresponding operating time is 1·77 seconds.

Calculation of Fault Current.

Correct relay application necessitates a knowledge of the fault current which can exist in each part of the network. As large scale tests are normally out of the question, resort has to be made to calculation. Generally it is sufficient to use machine transient reactances and to work upon the instantaneous symmetrical current. It is necessary, however, to cover faults between phases and from phase to earth.

The relay settings are first determined to give the shortest operating times at maximum fault values and checked to see operation will also be satisfactory at the minimum fault current expected. The latter refers to the condition where the smallest practical plant capacity is being used. Also changes in the switching conditions of the network must be taken into account, *i.e.*, certain circuit-breakers normally closed being opened or vice-versa.

Where a bulk supply is taken the authority concerned should be requested to furnish details of maximum and minimum fault values to the feeding point. Where the minimum condition results in fairly long operating times it is advisable to use the appropriate decrement factor in determining the fault current, except for remote parts of the network where the effect will be negligible.

By taking average values of the constants of machines of normal construction it is possible to provide curves to give a fair indication of the decrement factor to be expected. The curve shown by Fig. 21-8 is based upon the assumption that the generators are working at no load with minimum excitation prior to the inception of the fault, and that automatic voltage regulators are not left in operation. It should be understood that the percentage reactance must be based upon the actual kVA capacity of the generating plant being considered and *not* on the kVA base used for the purpose of short-circuit calculations. Where two or more generating stations are connected to the network the decrement must be determined for each station and applied to the fault current supplied by that station, the sum of these corrected fault currents being the final value.

This point also requires consideration when selecting operating times for back-up protection of alternators, since whilst the transient reactance may result in a short-circuit value of eight times full load current the sustained value might conceivably be limited to something just in excess of twice full load. In such cases it is often found that a more satisfactory arrangement is to use a constant or definite time limit relay rather than one having an inverse time characteristic.

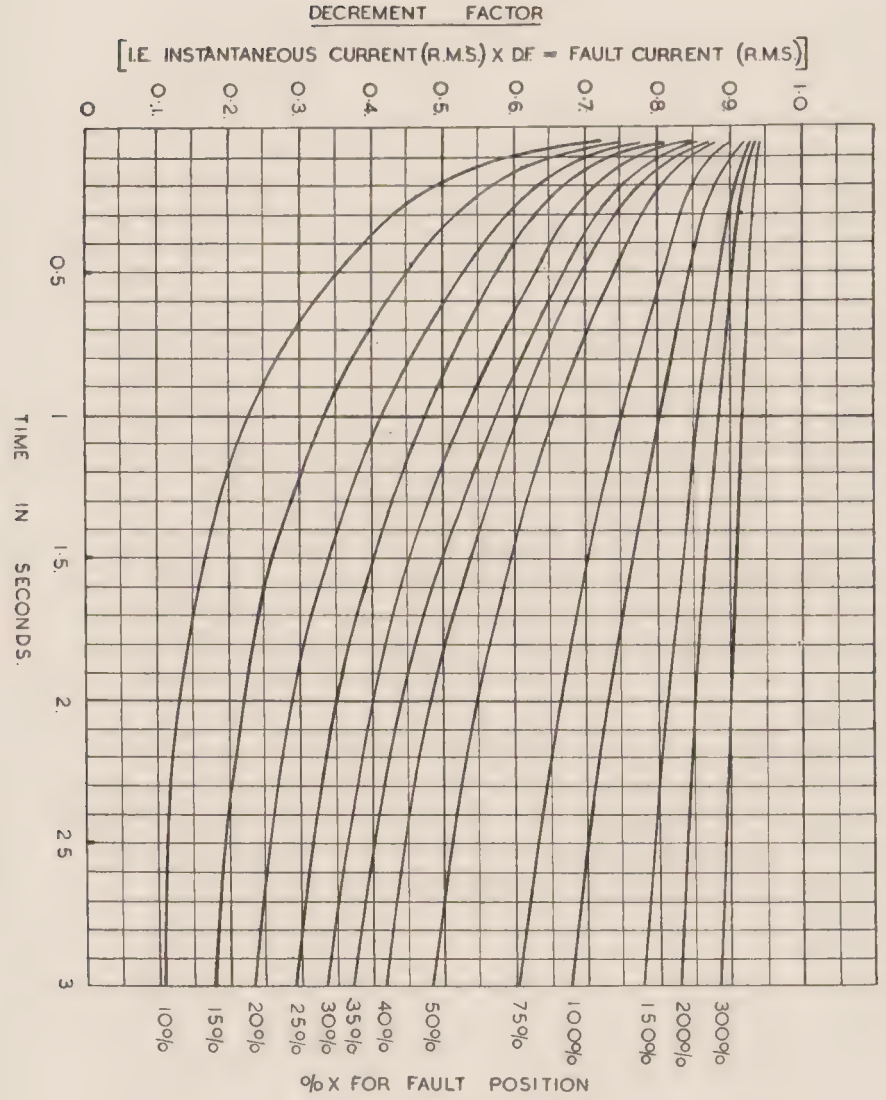


FIG. 21-8.

Decrement Curves.

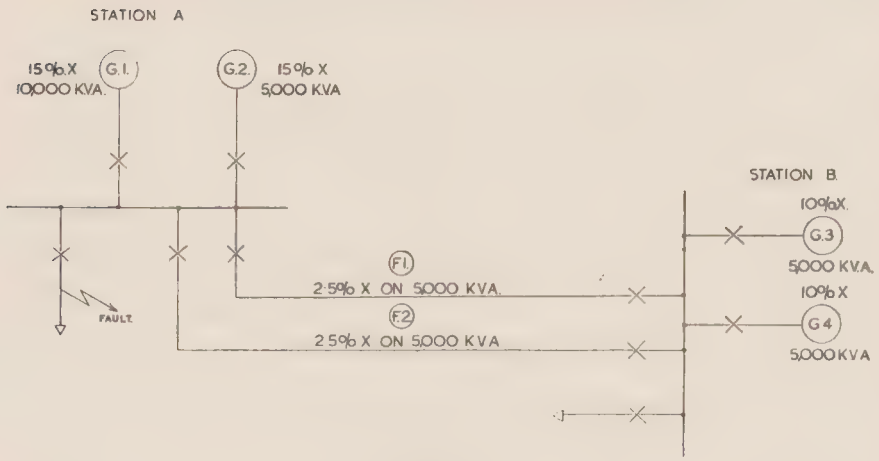


FIG. 21-9.

EXAMPLE 9.

A simple network is shown in Fig. 21-9 consisting of two generating stations and interconnector feeders to demonstrate the use of the decrement factor.

Assume fault at F.

The percentage transient reactances refer to the generator ratings.

Taking 10,000 kVA base for short circuit calculations we get

G_1	G_2	G_3	G_4	F_1	F_2
15	30	20	20	5	5

adding in parallel

G_1 and G_2	G_3 and G_4	F_1 and F_2
10	10	2·5

adding in series

$$G_3\ G_4 + F_1\ F_2 \quad (12{\cdot}5)$$

adding in parallel

$$G_1\ G_2 + (G_3\ G_4 + F_1\ F_2) \quad (5{\cdot}55)$$

$$\therefore \text{ S.C. kVA} = \frac{10{,}000 \text{ kVA}}{5{\cdot}55} \times 100 = 180{,}000 \text{ kVA}$$

$$\therefore \text{ Inst. symmetrical current} = \frac{180{,}000 \text{ kVA}}{11 \times 1{\cdot}73}$$

$$= 9{,}450 \text{ amperes (R.M.S.).}$$

This fault current is fed by two paths, from Station A and from Station B.

$$\text{S.C. current from A} = \frac{12{\cdot}5}{22{\cdot}5} \times 9{,}450$$

$$= 5{,}250 \text{ amperes}$$

$$\text{S.C. current from B} = 4{,}200 \text{ amperes}$$

Generating capacity, Station (A)

$G1 + G2 = 15{,}000$ kVA

Reactance to fault 10% on 10,000 kVA base

Converting to base of total capacity (15,000)

$$X\% = \frac{15{,}000}{10{,}000} \times 10 = 15$$

Assume short-circuit current is desired 0·5 second after fault, reading from Fig. 21-8 we get decrement factor of 0.45 and applying this to inst. symmetrical current (R.M.S.) we get:

$5{,}250 \times 0{\cdot}45 = 2{,}362$ amperes,

similarly Generating capacity, station (B)

$G3 + G4 = 10{,}000$ kVA

Reactance to fault 12·5% on 10,000 kVA base.

The latter in this case happens to coincide with the plant capacity. Reading from Fig. 21-8 we get decrement of 0·4.

Applying this to the inst. symmetrical current (R.M.S.) we get

$4{,}200 \times 0{\cdot}4 = 1{,}680$ amperes.

So that total fault current (R.M.S.) after 0·5 seconds from inception of fault is

$1{,}680 + 2{,}362 = 4{,}042$ amperes.

TYPES OF CHARACTERISTIC CURVES.

It is a cause of regret that there are so many relays upon the market having different characteristic curves.

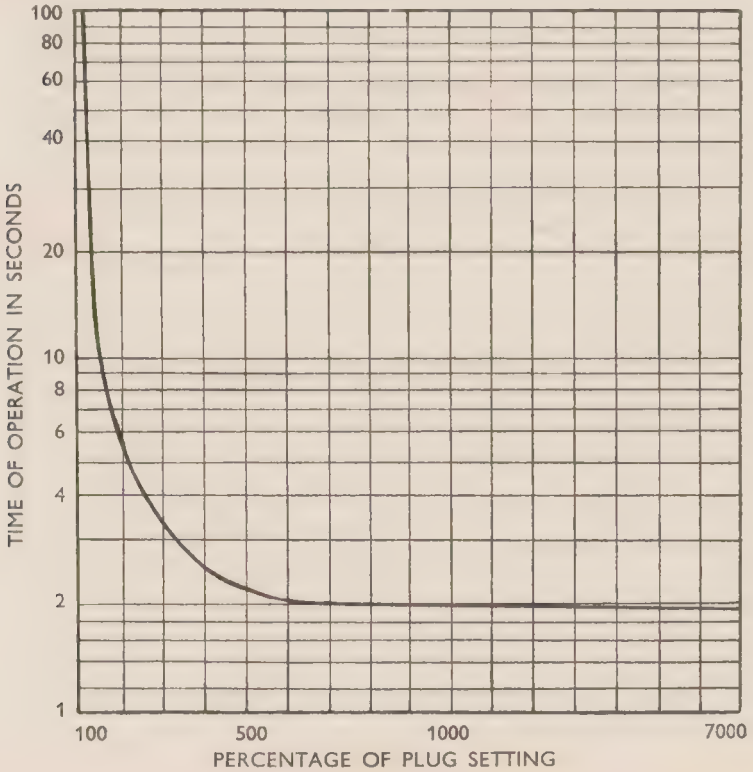


FIG. 21-10.

In addition to Figs. 21-1 and 21-2 already mentioned a further shape of curve in common use is shown by Fig. 21-10 and, of course, there are others available. A good deal of complication is avoided by using only one type of relay of a particular make for the whole of the network. In addition to the convenience of the common operating time characteristic it is reasonable to assume that the timing errors would not be so divergent. There is also the matter of resetting times and here considerable difference can exist. Consequently with a rapidly recurring fault inadvertent tripping can occur and this becomes more pronounced with automatic reclosing circuit-breakers.

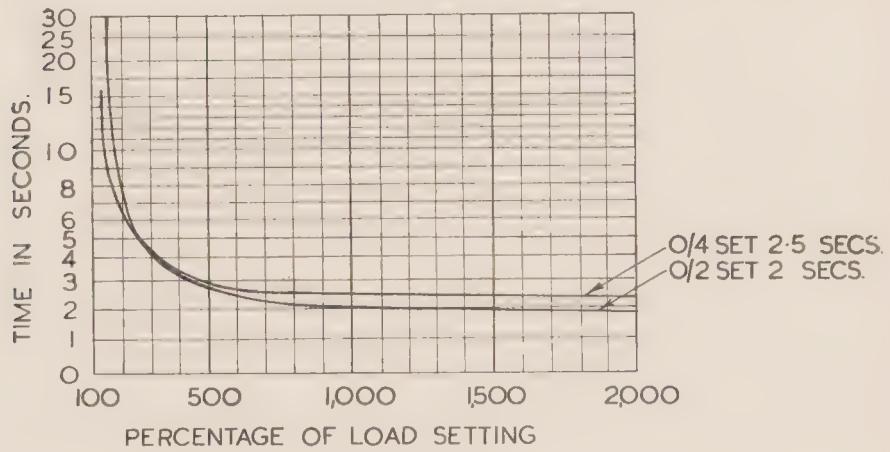


FIG. 21-11.

Where circumstances do not permit of standardising the type of relay care must be taken to see that the different characteristic curves permit sufficient time intervals at all parts of the curve covered by the working range. To do this properly a graphical method of comparison is essential. Similar precautions are also required when attempting to grade relays having saturation times of say 0/2 and 0/4 seconds respectively. Fig. 21-11 shows how the curve of a 0/4 second relay set at 2·5 seconds saturation time crosses that of a 0/2 second relay set at 2 seconds saturation time.

BIBLIOGRAPHY

" Applications and Limitations of the Inverse Time Overload Relay to the Protection of an 11 kV Network," J. W. Gallop and R. H. Bousfield, " Journal I.E.E.," Vol. 87, No. 524, Pages 113-134, 1940.

" Decrement Curves for Power Systems," C. F. Dalziel, " Electrical Engineering," Vol. 53, Pages 331-338, 1934.

Protective Gear Handbook, M. Kaufman, (Pitman and Sons).

" Network Relays –some observations on their Grading," A. Salzmann. " The Electrician," 11th and 18th March, 1949.

" Since this Chapter was first written the British Standards Institution have issued B.S. 142—1942, being a complete revision of the 1927 issue, entitled " Electrical Protective Relays." In view of the variation in characteristic curves mentioned in the foregoing pages, it is recommended that readers should refer to the new B.S. and particularly to its Appendix C, which sets down a provisional standard time-current curve as an objective at which it is hoped relay makers will aim when designing new relays or amending existing designs."

CHAPTER XXII

NEUTRAL POINT EARTHING

To earth or not to earth. This question has long been settled in this country in favour of earthing, preferably at one point only on each system. Thus there may be one neutral connection on the generator system, another on the higher voltage system used for transmission, and further connections with earth on any lower voltage systems used for secondary distribution. In distribution substations at 400/230 volts it is usual to earth one point at each, providing the substations are not interconnected.

The chief advantage claimed for the insulated neutral is that supply may be maintained on two healthy lines when a fault to earth occurs on the third line. This is more valuable on overhead line systems than on cable because an earth fault is not so likely to develop into one between lines. With cable networks, a sustained earth fault on one core can soon lead to a line to line fault. One core down to earth causes the potential of the two healthy lines to be raised above normal, increasing the stress on the insulation and in due course may lead to breakdown. On an overhead line, the greatest danger is due to an arcing ground at an insulator. This will produce transient surge voltages in both directions along the line, resulting in further insulation failures and possibly failures on switchgear and transformers.

Modern forms of protective gear permit the disconnection of faulty apparatus in the early stages of an earth fault. With an insulated neutral the current which can flow to earth is limited to the value of the capacity current, the neutral point being connected to earth through the star connected capacitances of each phase.

On the other hand, the advantages of the earthed neutral are many. In brief they include :—

(*a*) Persistent arcing grounds eliminated.

(*b*) Earth faults comprise a short-circuit between one line and earth.

(*c*) Protective gear can operate definitely on low earth fault currents.

(*d*) Voltage on sound lines held to line/neutral voltage.

(*e*) Induced static charges conducted to earth without disturbance.

The possibility of interference with communication circuits has caused the Electricity Commissioners to issue regulations which prohibit the earthing of high pressure systems at more than one point, except in special cases where the concurrence of the Postmaster-General is required.

Single point earthing permits earth fault currents to be limited by the insertion of a resistance or impedance in the earth connection. Nevertheless there is a school of thought which claims that the interference due to multiple earthing is more apparent than real and point to the advantages of having more than one point earthed when the loss of one neutral occurs due, for example, to shutting down one machine.

On the other hand, multiple earthing of generators may lead to circulating currents between machines. The earthing of one machine only maintains constant resistance between the neutral point and earth independent of the

number of generators running or, when no resistance is employed, limits the value of earth current to the capacity of one machine.

The actual connection to earth may be by one of the following methods :-

(1) Solid.
(2) Through a current limiting resistance.
(3) Through an arc suppression coil.
(4) Through a neutral compensator.
(5) Through a spark gap.

Direct or solid earthing may, on high voltage systems, result in very heavy fault currents flowing, as an earth fault constitutes a short-circuit across the phase concerned. It is important to recall that Ohm's law applies so that with a known value of resistance, the value of current can be ascertained very simply. There is no point in allowing this current to be much in excess of that required to operate the protective gear, thus relieving the shock on the system and reducing the fault current to be cleared by the circuit-breaker. Solid earthing is general at 400/230 volts and at voltages above 33 kV. For voltages intermediate, a current limiting device is employed. At 400/230 volts, earth resistance must be kept low as the voltage available is only 230 and it takes little resistance to severely restrict the earth current, possibly below that necessary for operation of protective gear.

Where a resistance is employed its value is important as it determines the degree of protection achieved. For generator circuits, it is usual practice to give the resistance a value which will permit the full load current of one generator—the largest—to pass with line to neutral voltage impressed across it. With present day relays and current transformers, a minimum setting of 15% is aimed at. Although lower values are possible, stability is sacrificed owing to the possibility of tripping due to spill currents on heavy through faults (see Chapter XX). Given a 15% setting, 85% of the generator winding is protected ; in other words, a fault in a generator winding at a point less than 15% from the neutral is not detected as insufficient current will pass to actuate the relay. The possibility of breakdown near the neutral point is, however, somewhat remote.

As an example, we may consider a single generator, the normal full load current of which is 500 amps. at 6,600 volts three-phase. The relay setting of 15% is equal to 75 amps. To obtain the value of resistance to pass full load current at line to neutral voltage, we have

$$R = \frac{V}{1{\cdot}73 \times I} = \frac{6{,}600}{1{\cdot}73 \times 500}$$

$$= 7{\cdot}65 \text{ ohms.}$$

Let us assume faults at 70%, 15% and 10% of the winding from the neutral point, and we find that the currents which will flow are

$$\text{At } 70\% = \frac{6{,}600 \times 70}{1{\cdot}73 \times 7{\cdot}65 \times 100} = 350 \text{ amps.}$$

$$\text{At } 15\% = \frac{6{,}600 \times 15}{1{\cdot}73 \times 7{\cdot}65 \times 100} = 75 \text{ amps.}$$

$$\text{At } 10\% = \frac{6{,}600 \times 10}{1{\cdot}73 \times 7{\cdot}65 \times 100} = 50 \text{ amps.}$$

This shows that with a relay setting of 75 amps. and a neutral resistance of 7.65 ohms, faults down to 15% are covered.

If we assume that there are a number of smaller machines running in parallel with the above, we find that these are protected to a greater degree. To determine the degree obtained, the formula is

$$\% \text{ of winding unprotected} = \frac{R \times I \times 100}{V}$$

where R = ohmic value of resistance.
I = primary out-of-balance amps.
V = line/neutral voltage.

If one of the smaller machines has a full load current of 300 amps., then 15% = 45 amps. and

$$= \frac{7{\cdot}65 \times 45 \times 100 \times 1{\cdot}73}{6{,}600} = 9{\cdot}1\% \text{ unprotected.}$$

If we assume now that future development demands the installation of a machine larger than any existing, it is interesting to ascertain the protection afforded by the existing resistance of 7·65 ohms. If the new machine has a full load current of 800 amps. then a 15% setting on the relay is 120 amps. Applying the formula above

$$= \frac{7{\cdot}65 \times 120 \times 100 \times 1{\cdot}73}{6{,}600} = 24\% \text{ unprotected}$$

or, 76% of the winding protected.

If this degree of protection is insufficient then steps must be taken to reduce the resistance.

The problem of neutral point earthing of transformers resolves itself into two parts—h.v. and l.v. That of h.v. earthing is for the protection afforded similar to that provided for machines. That of l.v. has the additional feature that it reduces to a minimum the danger to life in that earthing prevents the presence of any pressure above normal appearing at the l.v. winding, an important feature in domestic and industrial application.

In the J. & P. Transformer Book, the following expression is given to obtain the ohmic value permissible in the neutral conductor :—

$$ZN = \frac{E^2}{n \times kVA \times 1{,}000} \text{ ohms}$$

where E = Line Voltage
kVA = Rating of transformer
n = Neutral short-circuit current in terms of full load line current.

Assuming a 2,000 kVA transformer with an earth fault relay set at 40%, then related to the 400 volt side,

$$ZN = \frac{400^2}{0{\cdot}4 \times 2{,}000 \times 1{,}000} = 0{\cdot}2 \text{ ohms.}$$

By symmetrical component theory (see Chapter XIII) the zero phase sequence impedance where resistance is present in the neutral is

$$3R + j\,Xo$$

where R = resistance

Xo = zero phase sequence reactance

and, for the moment, assuming Xo to be sufficiently small to be ignored, then

$$\text{Neutral Fault Current} = \frac{3E}{3R}$$

$$= \frac{3 \times 231}{3 \times 0{\cdot}2} = 1{,}155 \text{ amperes.}$$

checking this,

F.L. Current 2,000 kVA at 400 V = 2,890 amps.

40% setting = 1,155 amps.

Where more than one machine or transformer operates in parallel, a study shows that the fault current differs from that when only one machine or transformer is in service. Where the earth resistance value is low, the change in current value may be important and affect relay settings. Where the resistance is high, the fault current is almost wholly limited by this, irrespective of the number of machines operating.

This may be demonstrated by symmetrical component theory where

Z_1 = Positive Phase Sequence Impedance.

Z_2 = Negative Phase Sequence Impedance.

Z_0 = Zero Phase Sequence Impedance.

Assuming there are six generators capable of single or parallel operation, that each is equal in output and characteristics, and that only one can be earthed at a time, the characteristics may well be

Z_1 = 20 per cent.

Z_2 = 14·6 per cent.

Z_0 = 6·4 per cent.

Now, with one generator operating alone its neutral being earthed through zero resistance, then

$$\text{Fault Current} = \frac{3E}{Z_1 + Z_2 + Z_0}$$

$$\frac{3E}{0{\cdot}2 + 0{\cdot}146 + 0{\cdot}064} = 7{\cdot}32\ E$$

Now let us assume all six machines are operating in parallel, but only one earthed, then

$$\text{Fault Current} = \frac{3E}{\left(\frac{0{\cdot}2}{6}\right) + \left(\frac{0{\cdot}146}{6}\right) + 0{\cdot}064}$$

$$= 24{\cdot}4\ E$$

This shows that in the latter case the fault current is approximately three times that of the first case.

The foregoing assumes zero resistance in the neutral. Let us now assume that two transformers each 2,000 kVA capacity are connected to operate singly or in parallel. Arrangements exist to earth one neutral through a resistance of 2 ohms. Bearing in mind that zero phase sequence impedance includes 3R, we have

$$Z_1 = 0 + j\,0{\cdot}009$$
$$Z_2 = 0 + j\,0{\cdot}009$$
$$Z_0 = 6 + j\,0{\cdot}009$$

With one transformer working alone, the total impedance to fault current will be the addition of the foregoing, *i.e.*,

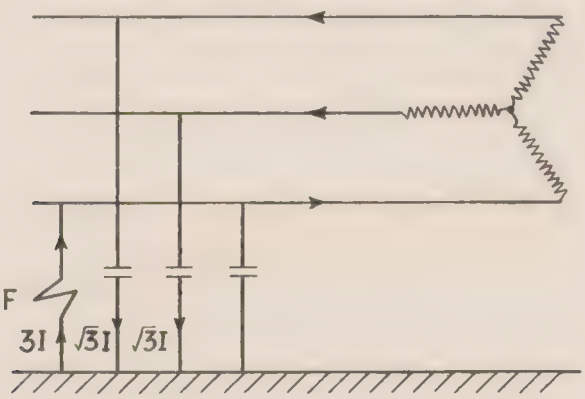
$$Z\ (\text{total}) = 6 + j\,0{\cdot}027 \text{ ohms.}$$

With two transformers operating in parallel, the total impedance will be

$$Z_1 = 0 + j\,0{\cdot}0045$$
$$Z_2 = 0 + j\,0{\cdot}0045$$
$$Z_0 = 6 + j\,0{\cdot}009$$

$$Z\ (\text{total}) = 6 + 0{\cdot}018 \text{ ohms.}$$

FIG. 22-1.



From the above, it is noted that the resistance is so large as to swamp reactance and the difference in fault current is negligible.

In a system in which the neutral is normally insulated, faults to earth do not constitute a short-circuit and disconnection of the faulty circuit is not necessary. An earth fault of low resistance does, however, bring the potential of the faulty phase to earth, leaving the two healthy phase 1·73 times their normal potential above earth. Such a condition may cause insulation breakdown, and in turn, short-circuits between phases. With a fault of high resistance, capacity currents may flow through the fault, the circuit being via the capacitances of the two healthy lines to earth and the fault. This condition is shown in Fig. 22-1, it being noted that the current in the fault is root-three times that of the capacitance current to earth of each healthy conductor. The fault condition described is very unstable, leading to what is termed an arcing ground.

Voltage oscillations set up may lead to further insulation failures on the network.

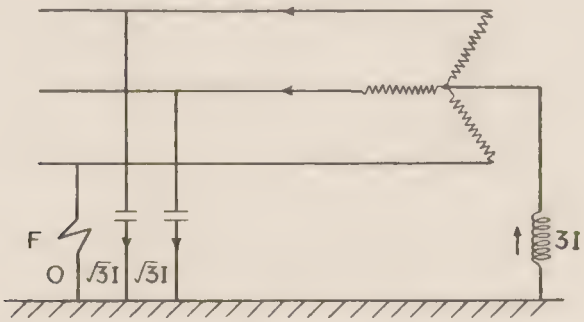


FIG. 22-2.

The capacitance current will lead the voltage of the faulty phase by nearly 90 degrees. If an inductance is connected in parallel with the capacitances, and this inductance is properly tuned, or resonated, the current in the fault will be cancelled out. This is what the arc suppression coil connected between the neutral point and earth does. The diagram for the arrangement is shown in Fig. 22-2. Tuning of the coil is necessary for each system individually. It may lead to some difficulty where system conditions may change widely but generally a tapped coil gives a close approximation to resonance to take care of system changes.

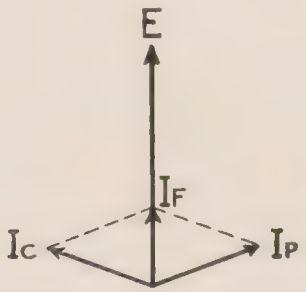


FIG. 22-3.

Fig. 22-3 is a vector diagram showing the condition of earth fault, where

I_c = Capacitance Current

I_p = Inductance Current

I_f = Current in Fault

Many engineers are loath to allow abnormal voltage conditions to exist on a network for extended periods, which is quite possible with arc-suppression coil earthing. If this condition can arise, it is essential that the insulation level of the switchgear be suitable. In general it may be assumed that the standard service ratings are suitable in so far as clearances and lengths of insulator are concerned but the electrical characteristics may be very different.

Practice on a number of installations is to allow the coil to remain in circuit for a short time (10 to 30 seconds) after which it is short-circuited automatically by means of an oil circuit-breaker. In one such system the coil remains in circuit for 10 seconds, and if a fault has not cleared itself in that time, the coil is short-circuited connecting the neutral direct to earth, permitting full fault current to flow and causing immediate operation of the protective gear.

After a further lapse of time, the coil circuit is re-established by the automatic opening of the circuit-breaker. This scheme naturally employs a number of relays and the use of automatic reclosing circuit-breakers.

On cable networks, earth faults can be regarded as permanent, once started, until the fault is isolated. The arc suppression coil permits the system to operate until isolation can conveniently be made. Overhead

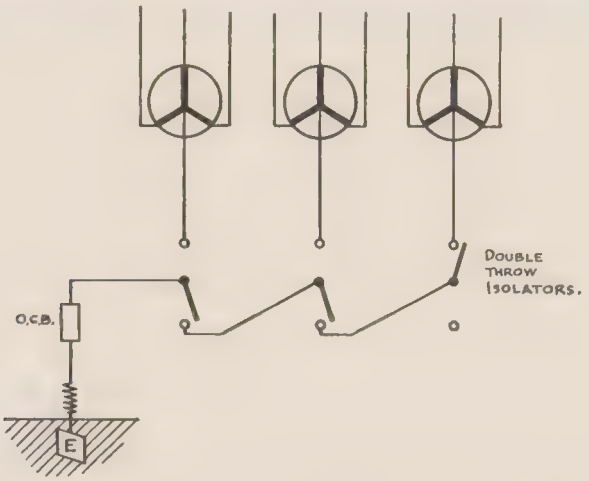


FIG. 22-4.—*Switching scheme to ensure that only one generator neutral is earthed.*

lines on the other hand suffer due to lightning, birds, parts of trees and so on, all causing faults of a transient nature. With an arc suppression coil, these are cleared immediately by the current limiting action. Whether to complicate the system by adding the short-circuiting breaker must depend on the network and the type of fault. Reference to a paper by Taylor and Stritzl* will indicate some of the problems of arc suppression earthing.

If arc suppression coils exist or are contemplated on a system, those enquiring for switchgear for use on that system should make this fact quite clear in the enquiry.

In order to ensure that only one neutral connection is made where a number of machines or transformers operate in parallel, a series of double throw isolators connected as shown in Fig. 22-4 can be installed. An oil circuit-breaker in the neutral connection is desirable, as should an isolator be opened at the moment of fault occurrence dangerous arcing may result. By installing a circuit-breaker, this can be opened before the isolator and closed after the isolator. If desired automatic protective features can be

* *See Bibliography*

fitted to the circuit-breaker. The difficulty with the single circuit-breaker is that it can be given no maintenance except by isolating the neutral.

Duplicate circuit-breakers have been installed on some systems to overcome this difficulty. Alternatively, a circuit-breaker can be connected in each machine neutral before connection to the common earth bar. A simple interlock between breakers will prevent multiple earthing. Circuit-breakers in the neutral connection should have a rated service-voltage equal to the phase voltage of the three-phase system to which it is connected. The breaking capacity must take into account the fault current likely to flow in the neutral connection. It has been shown on Page 492 that with alternators in parallel, the current can be greater than that which flows where a single machine is operating. It might be that this greater current is higher than the three-phase short-circuit current. Even where resistance is included in the neutral connection, the point needs noting because flashover across the terminals of a resistance have been known and this leads to the condition noted.

The earth connection proper is worthy of full consideration. At low voltages a low value of resistance is essential if protective devices are to operate. Common practice is to bury several earth plates or pipes in parallel in order to obtain low resistance values. The cross-section of the equipment must be such as to carry the maximum fault current. Earth plates, if used, may be copper or cast-iron, from three to six feet square. They should be buried in an upright position with charcoal or crushed coke to a thickness of about a foot or more. The strip connection to the plate or plates should be rivetted, or preferably welded, and not soldered, and should be of the same metal to avoid electrolysis. When pipes are used, these should be six to eight feet long and buried as deep as possible. They can be driven quite easily by electric or pneumatic hammers specially designed for the purpose

A low resistance is essential to keep down the potential gradient in the earth surrounding the plates or pipes under fault conditions. Most of the resistance exists in the immediate vicinity of the plates or pipes. Regular checking of the earth contact resistance is essential. It is by no means constant and alters with the amount of moisture in the soil and is therefore subject to seasonal variations.

BIBLIOGRAPHY.

"LINE PROTECTION BY PETERSEN COILS," H. W. Taylor and P. F. Stritzl, "Journal I.E.E.," Vols. 82 and 83, Nos. 496 and 503, 1938.

"SAFEGUARDS AGAINST INTERRUPTION OF SUPPLY," H. W. Clothier, B. H. Leeson & H. Leyburn, "Journal I.E.E.," Vol. 82, No. 497, May, 1938.

"THE PETERSEN EARTH COIL," S. Austen Stigant, "The Electrical Engineer," July 9th, 1937.

"DISTRIBUTION OF CAPACITANCE CURRENT," S. Austen Stigant, "The Electrical Times," July 4th, 1935.

Electrical Power, A. T. Starr (Pitman and Sons).

Switchgear Practice, A. Arnold (Chapman and Hall).

The J. & P. Transformer Book, S. Austen Stigant and H. Lacey (Johnson and Phillips, Ltd.).

NOTE.—The reader is referred to The J. & P. Transformer Book for details of earthing by neutral compensator on systems where a neutral is not available.

CHAPTER XXIII

AUTOMATIC VOLTAGE REGULATORS

In many ways, a description of the automatic voltage regulator is out of place in a switchgear book. As a piece of apparatus connected solely with machines, it would appear to be in its proper place when described in a work on machines. On the other hand, it is surprisingly rare that a purchaser buys his regulator as part of the machine contract, and in most cases it is included in the switchgear work.

This is a reasonable procedure only from one point of view, i.e., that the regulator is to be mounted on the switchboard, and connected to current and voltage transformers housed in the switchgear installation. From all other points of view, the procedure seems to be wrong, particularly where the switchgear manufacturer is not also a machine maker. That this is so is clear from the fact that before a regulator can be correctly supplied, a considerable amount of information concerning the machine or machines to be controlled has to be provided, involving in most cases a tender subject to confirmation as the switchgear maker cannot know whose machine will be ultimately ordered. By far the most satisfactory way would be for the regulator to be enquired for, and ordered with the machine, the switchgear maker being asked to provide space and mounting for the equipment.

As an example of the information required by a regulator manufacturer, a copy is included at the end of this chapter of the questionnaire issued by one maker, and which may be regarded as typical of all.

In view of the tendency to regard the voltage regulator as part of the switchgear equipment, the present chapter is included to outline the main principles of three makes. This outline will cover two forms, viz. :—

Vibrating Contact Type.
Rheostatic Type.

Two of the best known examples of the first type are the regulators made by The Metropolitan-Vickers Electrical Co., Ltd., and The British Thomson-Houston Co., Ltd., the latter being known as the "Tirrill" regulator. Both operate on the principle of alternately inserting and short-circuiting a predetermined amount of resistance in the field of the controlled machine.

The operation of The Metropolitan-Vickers' regulator may be grasped by reference to Fig. 23-1.

This shows diagrammatically a three-phase machine, with its exciter and controlled by an automatic regulator as it would be if the machine were one of a number in parallel and each machine provided with its own regulator.

T is a motor driven cam, the supply for which is from the voltage transformer K. By its rotation, this cam causes contact W to move up and down with constant frequency and amplitude. Contact X is spring supported and engages with contact W except when its movement is

arrested by a stop on the control arm Q. This latter carries an iron core I which is free to move up and down within the solenoid coil, which also includes a fixed iron core V. The solenoid coil is energised from the voltage transformer K. Connected across the exciter field resistance C, are contacts M, which close under the influence of springs except when coil N is energised. In normal operation the contacts W and X are making and breaking at the rate of about eight times per second.

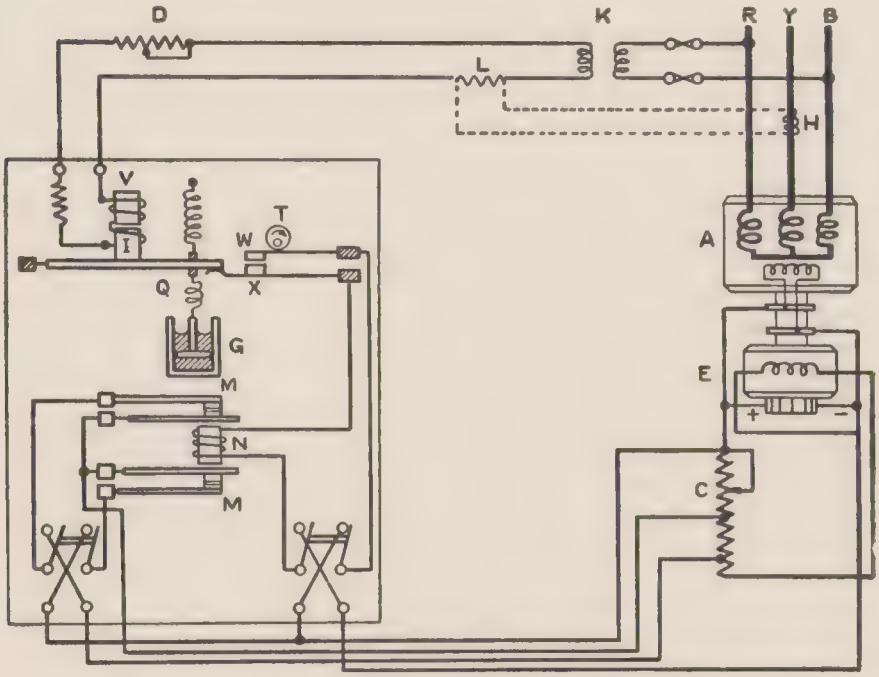


FIG. 23-1.

A. ALTERNATOR
C. EXCITER SHUNT FIELD RHEOSTAT
D. REGULATOR CONTROL COIL RHEOSTAT
E. EXCITER
F. REVERSING SWITCH FOR CONTACTS M
G. DASHPOT
H. CURRENT TRANSFORMER
I. MOVING IRON
K. VOLTAGE TRANSFORMER
L. COMPOUNDING RESISTANCE
M. REGULATOR MAIN CONTACTS
N. RELAY MAGNET
Q. MAIN CONTROL ARM
T. MOTOR DRIVEN CAM
V. FIXED IRON
WX. CONTACTS CONTROLLING RELAY MAGNET
Z. REVERSING SWITCH FOR CONTACTS WX

Diagram of Voltage Regulator with three-phase Alternator in parallel with others similarly connected (The Metropolitan-Vickers Electrical Co., Ltd.).

Such vibration causes contacts M to break and make with equal frequency, and thus the resistance C is alternately put into circuit and short-circuited. The average value depends on the proportion of time in which contacts M are closed. This time is controlled by the movement of the control arm Q which in turn is dependent on the voltage across the solenoid coil. Thus a drop in voltage gives a reduced upward pull on the core I and in consequence the control arm moves downward. This

holds contacts W and X open for a longer time and therefore contacts M close for a longer time. This has the effect of reducing the average value of the resistance C, and brings up the excitation until the voltage is sufficiently restored to prevent downward movement of the control arm. To enable the machine to respond to the change in the effective resistance, the dashpot G prevents the control arm moving too far before response.

The current transformer H and the corresponding resistance L are included to ensure stable operation of two or more regulators. The

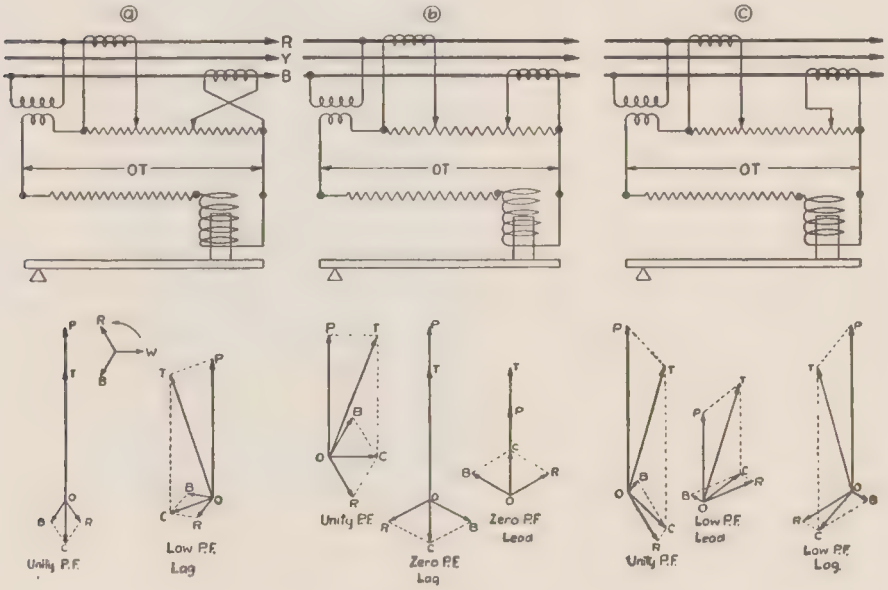


FIG. 23-2.

OT = VOLTAGE AT REGULATOR TERMINALS, MAINTAINED CONSTANT BY THE ACTION OF THE REGULATOR, AND IS PROPORTIONAL TO THE FAR-END VOLTAGE.

OP = VOLTAGE DUE TO THE POTENTIAL TRANSFORMER, PROPORTIONAL TO THE BUSBAR VOLTAGE.

OR = VOLTAGE DUE TO RED CURRENT.

OB = VOLTAGE DUE TO BLUE CURRENT.

OC = VECTOR SUM OF OR AND OB.

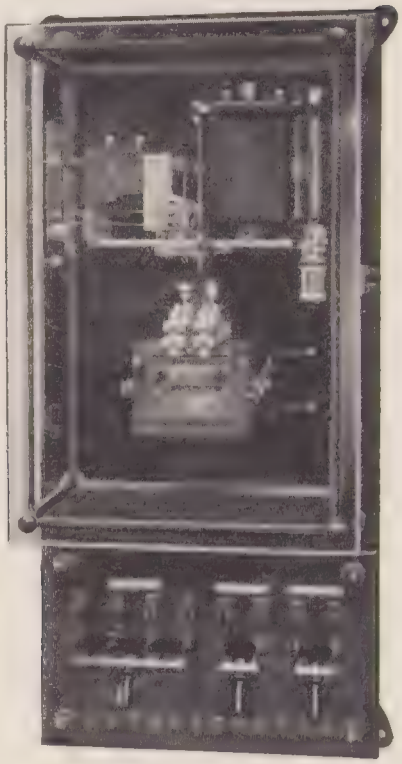
TP IS PROPORTIONAL TO THE VOLTAGE DROP IN THE LINE.

Diagram illustrating the operation of The Metropolitan-Vickers Line Drop Compensator. (a) for non-inductive drop, (b) for inductive drop, (c) for reactive and resistance drop.

voltage imposed across the resistance L is of such polarity that if the generator current tends to lag unduly, the current in the regulator control coil is measured and the regulator reduces the machine excitation.

A modified form of this regulator in which the controlling contacts are making and breaking circuits only during and immediately following a change of load, etc., is used for the control of large generators.

This normal inactivity of the contacts is obtained by a "follow up" control of a motor driven exciter field rheostat, the motor of which is controlled by auxiliary contacts on the automatic regulator itself.



Typical Voltage Regulator (The Metropolitan-Vickers Electric Co., Ltd.).

FIG. 23-3.

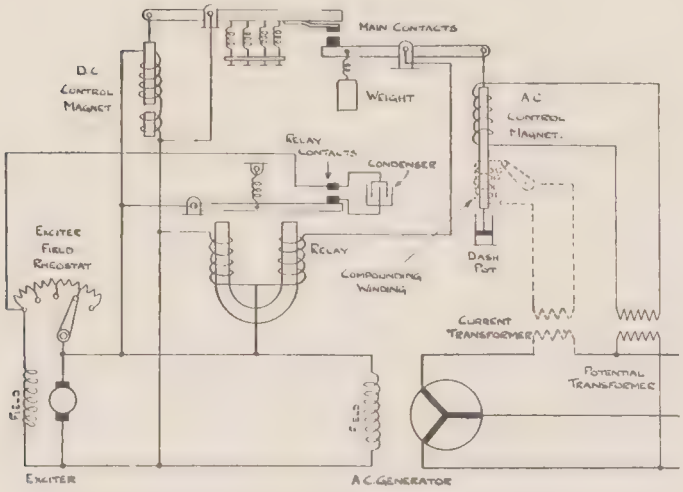


FIG. 23-4.—*Elementary Diagram of Tirrill Regulator (The British-Thomson Houston Co., Ltd.).*

The use of separate regulators for each machine when these have to operate in parallel ensures that abnormal conditions are taken care of, gives automatic control of power factor, and ensures the sharing of idle current with change of load.

Compensation for line drop may be made by injecting into the voltage control circuit of the regulator, a voltage proportional to and in phase with the voltage drop in the line. As is shown in Fig. 23-2 the provision for such compensation involves the use of two current transformers so connected to a portion of resistance in the control coil circuit that current

Tirrill Regulator with seven relays (The British-Thomson Houston Co., Ltd.).

FIG. 23-5.

derived from the transformers is passed through the resistance, causing a voltage drop across the resistance proportional to the current in the line, and of a phase corresponding to the power factor. A typical M.V.E. regulator is shown in Fig. 23-3.

The B.T.H. (Tirrill) Regulator was a pioneer in regulator design in this country. An elementary diagram is given in Fig. 23-4. Here the upper main contact end is given a vibratory motion. The core of the A.C. control magnet, which is mechanically associated with the steady lower contact, is balanced in any position over its range of travel when current corresponding to normal voltage passes through the coil. Thus at low loads, when the core has been brought to the higher end of its range of travel, the main contacts are out of contact during most of the time of the beat.

Conversely, at high loads, the contacts are in contact for most of the time of the beat. As in the earlier description of the M.V.E. type the

closing and opening of the main contacts operates the relay coil to make and break the relay contacts which insert and short-circuit resistance in the exciter field circuit. A typical Tirrill regulator, with seven relays, is shown in Fig. 23-5.

Both the foregoing types may be regarded as expensive for small machines, and to overcome this, the two companies named now offer a less expensive regulator of the rheostatic type suitable for use with D.C.

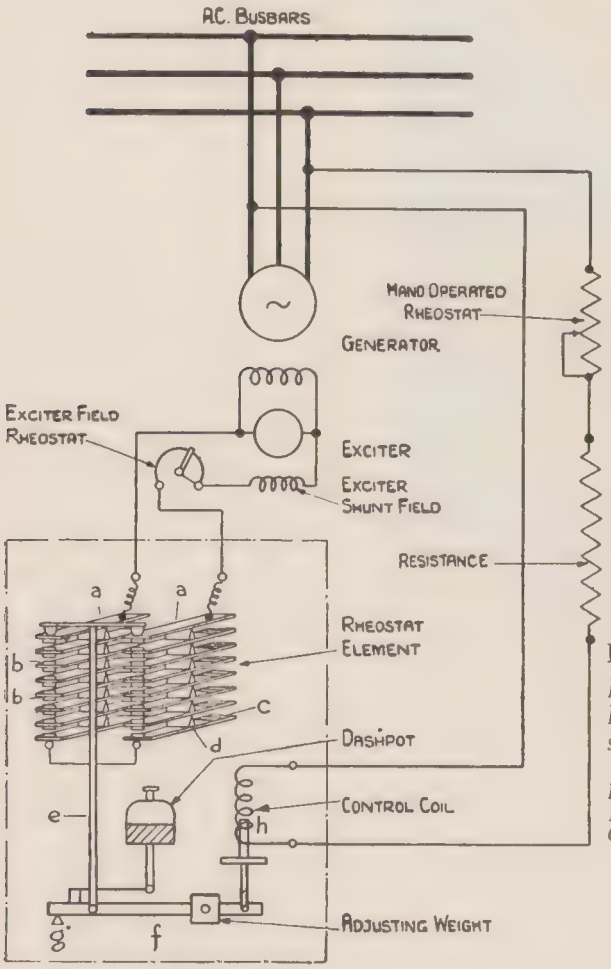


Fig. 23-6.

Elementary Diagram of Rheostatic Regulator for small machines

(The Metropolitan-Vickers Electrical Co., Ltd., and The British Thomson-Houston Co., Ltd.).

machines up to about 25 kW operating alone (i.e., not in parallel with another) and for A.C. machines up to about 250 kW. In the latter case a separate regulator is needed for each machine when these run in parallel. It is also recommended that power-factor compensation should be provided.

This form of regulator, which is suitable where extreme accuracy is not required, comprises a metal-carbon rheostat consisting of two stacks of rectangular carbon plates, shown as (a a) in Fig. 23-6. Series or parallel connection of the stacks is possible.

It will be seen that near the front edge of each carbon plate passing right through it, is a silver contact (b b), while near the rear edge there is a high resistance spacer (c). A fulcrum under each plate is arranged so that each plate can be rocked.

The tilting of the stacks is under the control of the solenoid (h) which is energised from the circuit under regulation (note that a voltage transformer is necessary above 440 volts) and actuation is via the lever (f) and rod (e), with a dashpot to damp the action and prevent bursting.

It will be seen, therefore, that when the stacks are tilted forward a path of negligible resistance is provided through the silver contacts, and when tilted backwards, a high resistance path is formed.

Under normal operating conditions, a proportion of the plates are tilted forward (approximately half), this position giving voltages within the set limits. Any rise in the regulated voltage causes the silver contacts to open in succession until the resistance in the stacks is increased sufficient to restore voltage to its correct value.

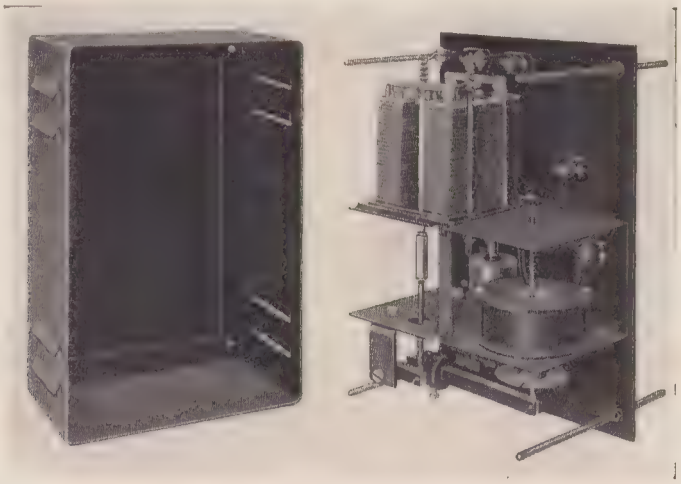


FIG. 23-7.—*Rheostatic Regulator for small machines (The Metropolitan-Vickers Electrical Co. Ltd., and The British Thomson-Houston Co., Ltd.).*

Conversely, a fall in voltage causes more contacts to close and so again restore the voltage.

The hand operated rheostat connected in the control coil circuit, enables the normal voltage to be adjusted. Fig. 23-7 also illustrates this form of regulator.

One of the best known forms of rheostatic voltage regulator is that manufactured by Messrs. Brown-Boveri & Co., Ltd.

This regulator comprises these principal parts :—

(1) The motive system providing the force to move the rolling sectors.
(2) The regulating resistance necessary to vary the excitation.
(3) The damping system and elastic recall.

The motive system and regulating resistance are shown in Fig. 23-8.

The motive system of an A.C. regulator is based on the Ferraris principle. An annular laminated core carries two windings (a) and (b).

The winding (b) with series resistance (R) is connected in parallel with the highly inductive winding (a), and in series with this parallel circuit are the adjusting resistances (U) and (u^1). The windings are electrically at right angles, and by virtue of the phase displacement between the currents in them a rotating field is produced.

The aluminium drum (c) is placed in this field and is subject to a torque which it transmits to the spindle of the motive system. The main spiral spring (f) has its inner extremity connected to the front part of the spindle, its outer extremity being connected to the spring housing. In order that the resultant torque on the spindle may be constant for all positions of the drum, an auxiliary spring (n), also connected to the spindle, is provided to compensate the otherwise sloping characteristic of the main spring.

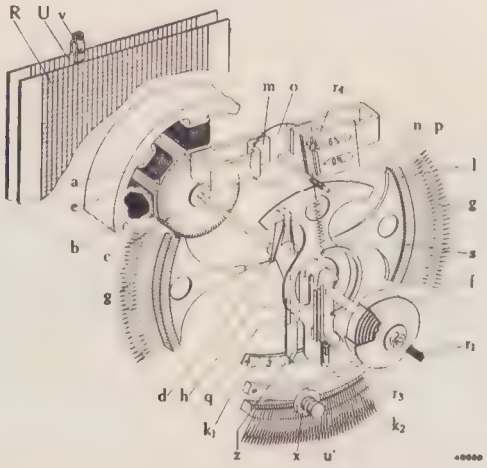


FIG. 23-8.—*Brown-Boveri Voltage Regulator (Rheostatic Type) (Brown-Boveri & Co., Ltd.).*

The electrical and mechanical torques are in opposition and are exactly balanced when the voltage at the regulator terminals has the prescribed value.

By adjustment of the auxiliary spring two conditions can be achieved :—

(*a*) A condition which gives the regulator a perfectly level deflection volts characteristic without external influence. This adjustment is used for machines operating singly, or in exceptional cases for parallel operation where polygon connected current transformers are used for stabilisation.

(*b*) A condition which gives the regulator a falling characteristic which is used for parallel operating instruments stabilised by current transformers (see Fig. 23-9). When the regulator is in equilibrium the drooping characteristic is fully compensated by the influence of a current transformer connected in one of the phases between the machine and busbars ; thus a level voltage characteristic is obtained. The effect of this

current transformer depends on both magnitude and phase of the load current, the object of which is to influence excitation by the wattless current. Thus three results are obtained, namely, constant voltage, automatic power factor control and stable parallel operating conditions.

The regulating resistance comprises coil elements (g) connected to contact blocks (1). These elements are connected in series and the contacts

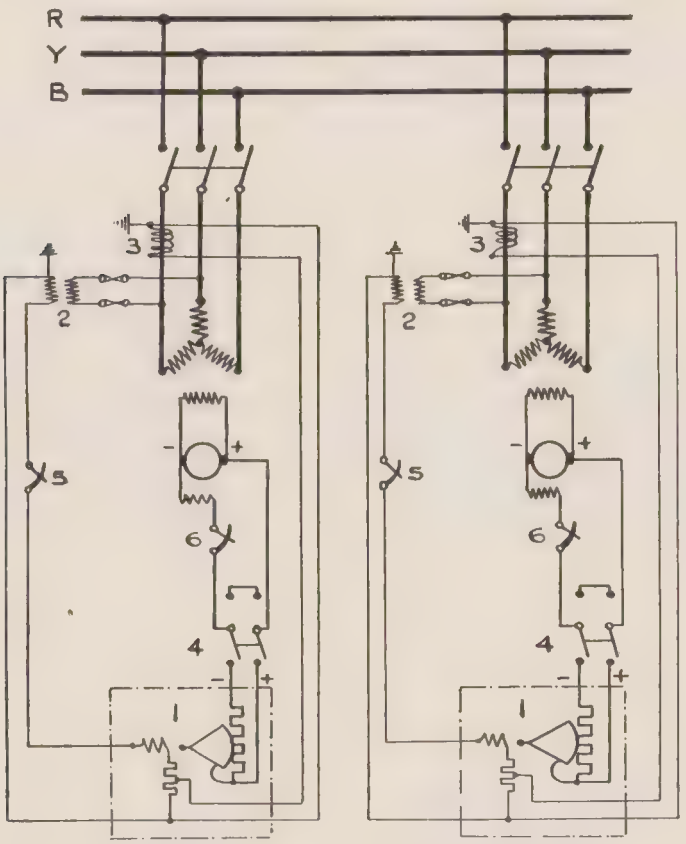


FIG. 23-9.

are laid out on arcs of a circle concentric to the axis of the apparatus. The contact sectors (s) roll on the interior surface of the contact blocks which are grooved to provide a track. The steel point of each sector is mounted in a jewelled cup carried on a spring (d) and is guided by the movements of the spindle so as to travel through corresponding arcs of a circle, causing displacement of the point of contact on the blocks. Spring (d) provides sufficient pressure to give good contact. Reaction to this pressure is

compensated by the reaction of the sector diametrically opposite, friction being thus almost entirely eliminated; therefore the force required to move the sectors is very slight.

The elastic recall device comprises the recall spring (q) and the damping system. The latter is composed of the toothed segment (p) which drives the pinion of the damping disc (o). The disc, which is of aluminium, moves between the poles of the permanent magnets (m) which exert a braking effect. The effect of the recall device is to allow the drum to rotate to its end positions under violent load fluctuations and yet, by the recall spring (q), the motive system is brought back in time, before the end of the regulating process, to its new position of equilibrium.

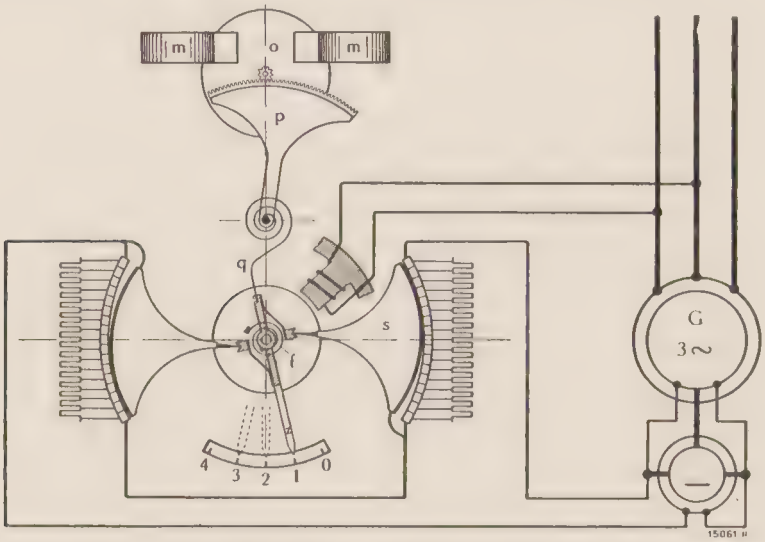


FIG. 23-10.—*Simplified diagram of Brown-Boveri Regulator (Brown-Boveri & Co., Ltd.).*

The process of voltage regulation by the Brown-Boveri regulator briefly described above, may be followed in conjunction with Fig. 23-10, which is a simplified diagram only.

With the alternator at full load and standard voltage, it is assumed that it requires excitation at 100 volts. At this condition the contact sectors are situated so that the pointer (z) is approximately at position (1), i.e., the regulating resistance is nearly all short-circuited. So long as the alternator voltage remains at its proper value, the torque on the drum will counterbalance the torque due to the springs and the moving system will be in equilibrium. A drop in load on the machine causes the voltage to rise and with it the torque on the drum, which will now exceed that of the springs, and acts on the motive system thereby moving the pointer (z) to the left. Movement at first is unhampered and very rapid, but it causes tightening of the recall spring (q) between the motive system and the damping segment, which latter can only follow slowly. The recall spring thus produces an opposite torque bringing the motive system to rest in say position (3). This movement has inserted a great part of the

regulating resistance and the exciter voltage has been reduced to say 50 V. The alternator voltage drops and the electromagnetic torque diminishes proportionately. The tightened recall spring, added to the effort of the main spring, can now overcome the electromagnetic torque, returning the motive system to say position (2) sufficient to maintain standard voltage at the alternator terminals. As in the case of other regulators, line drop compensation can be provided. A typical regulator is shown in Figs. 23-11 and 23-12.

This form of regulator can be adapted as an automatic power factor regulator, an automatic synchroniser, frequency matcher and other special applications, all of which are extremely interesting, but beyond the scope of the present work.

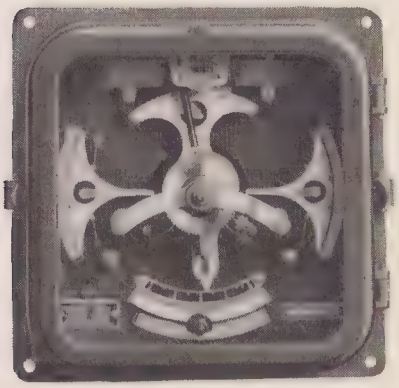


FIG. 23-11.
Brown-Boveri Voltage Regulator (Brown-Boveri & Co., Ltd.).

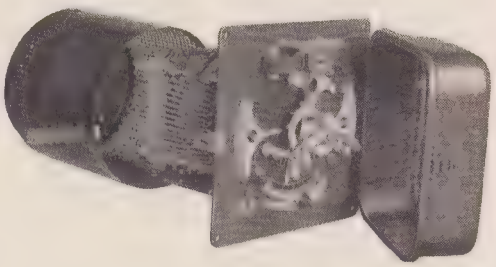


FIG. 23-12.
Brown-Boveri Voltage Regulator opened to show moving system and resistances (Brown-Boveri & Co., Ltd.).

As in the case of the vibrating contact type, the Brown-Boveri Company have available a small unit which has about half the regulating capacity of the regulator illustrated in Fig. 23-11. This instrument usually covers the requirements of machines up to approximately 200—250 kVA and will limit sustained voltage variations to ± 1%.

This unit operates on exactly the same principle as the larger type described earlier, i.e., on the principle of an aluminium drum free to move in the field produced by two windings, the currents in which are practically in quadrature. One contact sector is rolled over the segments connected to the regulating resistance. A typical regulator of this type is shown in Figs. 23-13 and 23-14, while typical diagrams of connections for individual operation and parallel operation are given in Fig. 23-15.

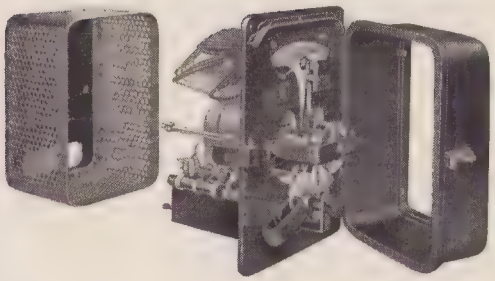


FIG. 23-13.
Brown-Boveri Regulator for small machines
(Brown-Boveri & Co., Ltd.).

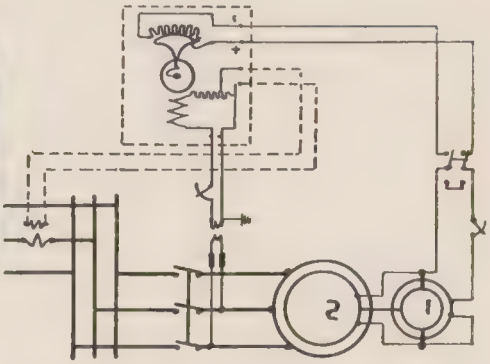
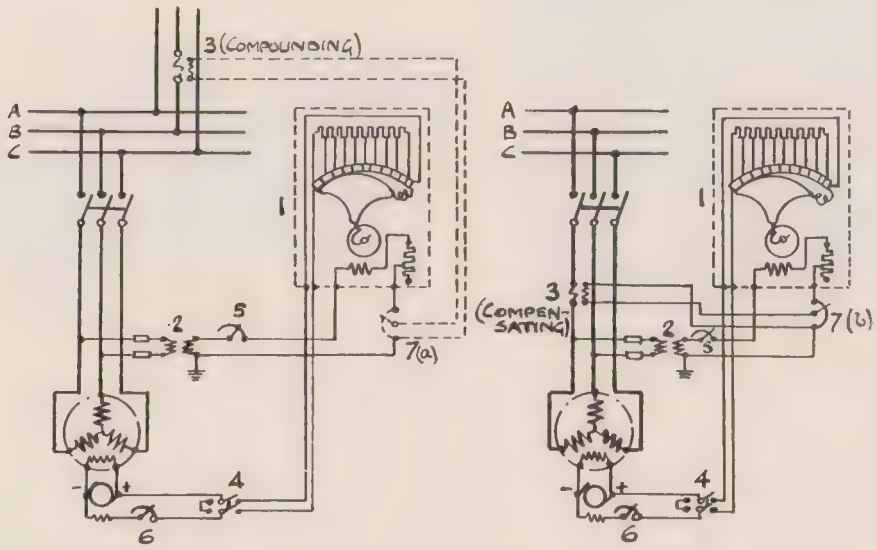


FIG. 23-14.
Brown-Boveri Regulator for small machines
(Brown-Boveri & Co., Ltd.).



1 - VOLTAGE REGULATOR
2 - POT TRANSFORMER (ABOVE 230 VOLTS)
3 - CURRENT TRANSFORMER
4 - CHANGE-OVER SWITCH
5 - ADJUSTING RHEOSTAT
6 - EXCITER FIELD RHEOSTAT
7 - COMPOUNDING (a) OR COMPENSATING (b) RHEOSTAT

FIG. 23-15.—*Brown-Boveri Regulator Diagrams for Individual and Parallel Operation (Brown-Boveri & Co., Ltd.).*

TYPICAL AUTOMATIC VOLTAGE REGULATOR QUESTIONNAIRE.

(1) Capacity of alternator in kW and kVA.
(2) Alternator voltage.
(3) Frequency and number of phases.
(4) How driven (turbo, engine, water, etc.).
(5) If engine or water driven state maximum percentage speed variation.
(6) Exciter capacity in kW and how driven.
(7) How is exciter field excited (shunt or separately excited).
(8) Confirm that the exciter field rheostat is capable of regulating the alternator voltage from 60% of normal at no-load to maximum overload, with the alternator main field rheostat (if any) in one fixed position, and that the exciter is stable over this range.
(9) Exciter voltage required to give 60% of normal alternator voltage at no-load.
(10) Exciter field current for conditions as (9) above.
(11) Exciter field resistance (a) cold, (b) hot.
(12) Type of exciter field rheostat ("straight" or "circular"). "Straight" means a double rheostat short-circuited by the slider from the centre downwards. "Circular" means a single rheostat short-circuited by the slider from one end.
(13) Exciter volts with alternator on no-load (cold).
(14) Exciter volts with alternator at maximum overload (hot).
(15) Exciter field current with alternator at maximum overload. (These last three particulars are to be taken with the alternator running at normal speed and voltage, and with the alternator main field rheostat, if any, in the one fixed position of question 8).
(16) Rotation to raise volts required for regulator rheostat.
(17) Confirm that the range of excitation provided is sufficient to cater for the maximum percentage speed variation of the prime mover.
(18) Any other details regarding excitation.

BIBLIOGRAPHY

The Switchgear Handbook, W. A. Coates and H. Pearce (Pitman), Vol. I.

Electric Switch and Control Gear, C. C. Garrard (Benn Brothers).

CHAPTER XXIV

THE USE OF CURRENT-LIMITING REACTORS

It has been demonstrated in Chapter XIII that the magnitude of the short-circuit current which can appear at a given point under fault conditions depends principally upon the reactance in the circuit up to the fault. In many cases, in order to take advantage of standard switchgear or to protect older switchgear due to additional plant being added, it is advantageous to deliberately add reactance. Two forms of reactor are in use for this purpose, the iron-cored reactor or the air-core type. It is not the purpose of this Chapter to consider these designs as such but it is appropriate to note that an essential feature is a straight line characteristic up to the maximum value of current which can pass through the coil.

The rating of a current limiting reactor is usually given as a percentage This is the ratio of the voltage drop across the reactor to the normal rated voltage when a stated current is flowing at normal frequency. In the case of a three-phase circuit, a reactor having a rating of 20 per cent. will, if used on a 200 ampere 6,600 volt circuit, have a drop of 765 volts when 200 amperes are flowing, *i.e.*, 20 per cent. of line-to-neutral volts (6,600/1.73).

In general, added reactance should be located at those points in a network where they can be most effective. It should be kept in mind that with loads of poor power factor, the reactor tends to interfere with regulation.

Very few occasions arise where it is necessary or desirable to add reactance in a generator circuit. In modern machines, sufficient inherent reactance is allowed in the design to enable it to withstand the forces of short-circuit. If modern machines are to be paralleled with older ones, a case may arise for adding reactance in the circuit of those older machines to protect them and to obtain roughly the same characteristic as the new machines.

Feeder reactors are not an economical proposition as often so many feeders are involved. A good case however can be that of a group feeder (see Chapter II) where it is essential to protect a group of circuit-breakers of insufficient breaking capacity. Similarly a tie between new and old switchgear may profitably include reactors to avoid replacement of old circuit-breakers. The busbar connection scheme for group feeder reactors has been shown in Fig. 2-9.

Feeder reactance has the advantage of localising the disturbance to the feeder on which trouble occurs, leaving the rest of the plant undisturbed. This is of importance where synchronous plant is in service. The usual value of reactance for group feeders is of the order of 3 to 5 per cent. based on the normal current loading of the circuit. It is important to note that whereas as at (or near) unity power factor, the effect on regulation is negligible, at low power factors, serious interference may occur. The following table gives an indication of the effect.

Reactance added %	Regulation Increase			
	1·0 P.F.	0·9 P.F.	0·8 P.F.	0·5 P.F.
1	—	0·4	0·5	0·75
2	—	0·75	1·15	1·5
3	—	1·25	1·75	2·4
4	0·1	1·6	2·4	3·25
5	0·15	2·2	3·0	4·1
6	0·2	2·7	3·75	5·0
7	0·25	3·2	4·5	6·0
8	0·3	3·75	5·15	7·0
9	0·4	4·3	5·8	8·0
10	0·5	5·0	6·6	9·0

Power factor itself will also be affected by added reactance and the extent of this may be determined from the curve Fig. 24-1.

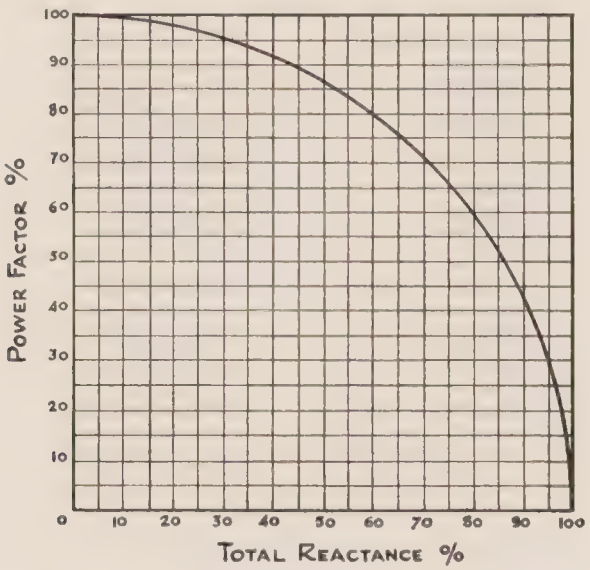


FIG. 24-1.—*Effect of added reactance on power-factor.*

The remaining location for the introduction of reactance is in the busbars.

In this position reactors not only sectionalise the busbars, but the system also. It is essential to ensure that this sectionalising is not destroyed by tying the sections solidly together at a remote point. Should such a tie be necessary, then an examination is essential to ascertain if there is ample reactance in the feeders to give the necessary protection. The introduction of busbar reactors gives protection in the event of feeder, busbar or generator short-circuit, the degree of protection being greater as the number of busbar sections is increased. If the reactors are suitably chosen, trouble

on one section will not disturb the voltage on adjacent sections due to current flowing through the reactors to the faulty section. At the same time, the reactors must permit the interchange of current to equalize the loading on the generators. It will be clear that not only will there be a voltage drop across busbar reactors but there will also be a difference in phase angle between bus sections, a difference which may be appreciable between the extreme ends of a large system.

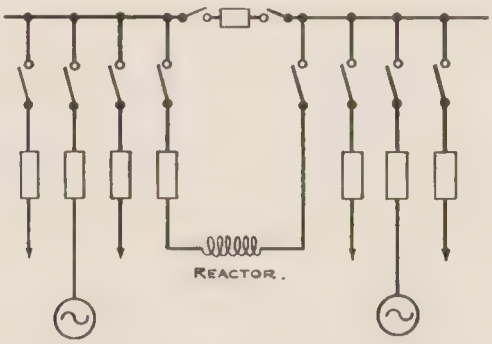


FIG. 24-2.—*Busbar Reactor with short-circuiting switch.*

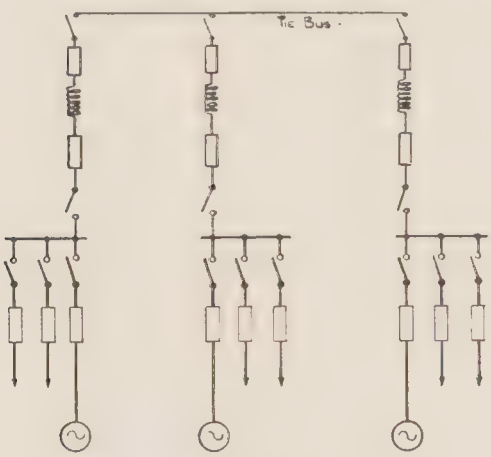


FIG. 24-3.—*Tie Busbar System.*

The rating of a busbar reactance is usually such as to allow a transfer of power equal to 25 to 30 per cent. of the generator capacity connected to each section. The current normally carried is generally small and, therefore, so are the losses, and regulation is improved.

Various methods of connecting reactors in the busbars are shown in Figs. 24-2, 24-3 and 24-4.

The following examples will demonstrate the methods to be employed for determining the effect of added reactance and for determining what value of reactance is necessary to achieve a desired result.

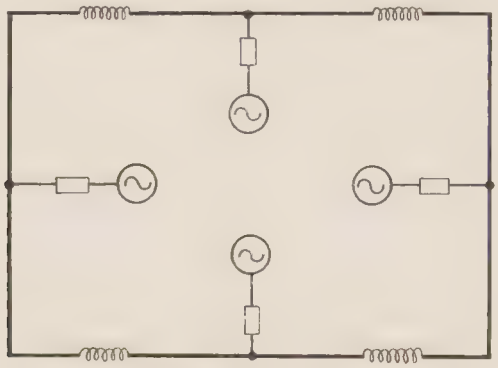


FIG. 24-4.—*Reactors in Ring Busbars.*

As an example of the effect of added reactance, let us assume a system as shown at (*a*) in Fig. 24-5. Here, a fault at the point X on the feeder F will be fed by the three generators and its value limited only by the reactance of the machines. The fault value is calculated as follows :—

Base kVA = Total plant capacity = 42,000 kVA.

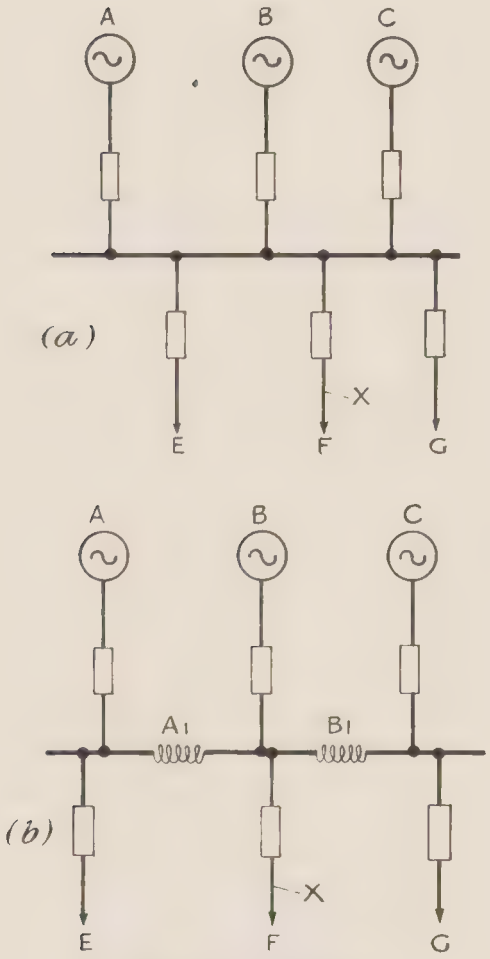
Reactance Gen. A on base kVA $= \frac{42{,}000 \times 10}{10{,}000} = 42\%$

Reactance Gen. B on base kVA $= \frac{42{,}000 \times 12}{20{,}000} = 25{\cdot}1\%$

Reactance Gen. C on base kVA $= \frac{42{,}000 \times 10}{12{,}000} = 35\%$

Combined reactance A B C $= \frac{1}{\frac{1}{42} + \frac{1}{25{\cdot}1} + \frac{1}{35}} = 10{\cdot}8\%$

Instantaneous S.C. MVA $= \frac{42{,}000 \times 100}{10{\cdot}8 \times 1{,}000} = 390$ MVA



A = 10,000 kVA 10% REACTANCE.
B = 20,000 kVA 12% REACTANCE.
C = 12,000 kVA 10% REACTANCE.
A1 = 20% ON 20,000 kVA.
B1 = 20% ON 20,000 kVA.

Fig. 24-5.

If, now, reactors A1 and B1 are added in the busbars as shown at (*b*), Fig. 24-5, we note that while machine B feeds directly into the fault, Machine A and C now feed into it via the reactances A1 and B1 respectively.

Converting the added reactance values to the base kVA we get

$$\text{Reactors A1 and B1 on base kVA} = \frac{42{,}000 \times 20}{20{,}000} = 42\% \text{ each}$$

and the combined reactance will now be,

$$\frac{1}{\frac{1}{42+42} + \frac{1}{25{\cdot}1} + \frac{1}{35+42}} = 15{\cdot}43\%$$

and the fault value will be

$$\text{Inst. S.C. MVA} = \frac{42{,}000 \times 100}{15{\cdot}43 \times 1{,}000} = 270 \text{ MVA}$$

As an example demonstrating how to determine an appropriate value of added reactance to achieve a desired result, let us assume that a small existing generating station is to be extended to allow for taking a bulk supply from another source. The ultimate diagram is that shown in Fig. 24-6.

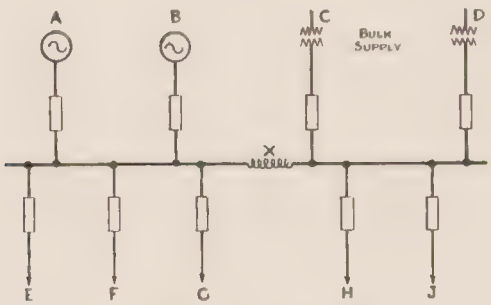


FIG. 24-6.

The existing switchgear is rated at 150 MVA based on the generating plant alone, which shows that a fault of 108 MVA can arise due to this source. The addition of two 10,000 kVA transformers each of 10 per cent. reactance, means that the existing switchgear is inadequate, as the two transformers in parallel will contribute a further 200 MVA, making 308 MVA in all. It is proposed therefore to instal a reactor at X, to safe-

guard the existing switchgear. The reactance value will be determined thus,

$$\text{kVA base} = 10{,}000 \text{ kVA}$$

$$\text{Total resultant reactance to ensure existing gear at 150 MVA} = \frac{100 \times 10{,}000}{150{,}000} = 6{\cdot}66\%$$

$$\text{Reactance (combined) of existing machines} = 9{\cdot}3\%$$

$$\text{Reactance (combined) of new transformers} = 5\%$$

$$\text{Value of Reactance X} = \frac{1}{9{\cdot}3} + \frac{1}{5 + X} = \frac{1}{6{\cdot}66}$$

$$\therefore \frac{1}{5 + X} = \frac{1}{6{\cdot}66} - \frac{1}{9{\cdot}3}$$

$$= \frac{9{\cdot}3}{61{\cdot}94} - \frac{6{\cdot}66}{61{\cdot}94}$$

$$= \frac{2{\cdot}64}{61{\cdot}94}$$

$$= \frac{1}{23{\cdot}45}$$

$$\therefore 5 + X = 23{\cdot}45$$

$$X = 23{\cdot}45 - 5$$

$$X = 18{\cdot}45\% \text{ on } 10{,}000 \text{ kVA.}$$

This may be checked as follows,

$$\frac{1}{\frac{1}{9{\cdot}3} + \frac{1}{5 + 18{\cdot}45}} = 6{\cdot}66\%$$

$$\text{Inst. S.C. MVA} = \frac{10{,}000 \times 100}{6{\cdot}66 \times 1{,}000} = 150 \text{ MVA}$$

Having added the busbar reactor, it is clear that this will act to limit the fault feed from the two existing machines into a fault on feeders H or J.

Previously we found that the total short-circuit values was 308 MVA without the reactor. The new fault value at H or J will now be,

$$\frac{1}{\frac{1}{9{\cdot}3 + 18{\cdot}45} + \frac{1}{5}} = 4{\cdot}23\%$$

$$\text{Inst S.C. MVA} = \frac{10{,}000 \times 100}{4{\cdot}23 \times 1{,}000} = 236 \text{ MVA}$$

for which circuit-breakers of 250 MVA will suffice instead of 350 MVA which would have been necessary without the reactor.

BIBLIOGRAPHY.

Switchgear Handbook, Vol. II, W. A. Coates and H. Pearce (Pitman and Sons, Ltd.).

Electric Power System Control, H. P. Young (Chapman and Hall).

Electric Power Stations Vol. 2, T. H. Carr (Chapman and Hall).

" Application of Current Limiting Reactors to Power Systems," " M.A.I.E.E.," " The Electrical Engineer," December 29, 1939.

" The Duplex Reactor and its Application," E. G. Merrick, " General Electric Review," September, 1944.

CHAPTER XXV

OUTDOOR SWITCHGEAR FOR RURAL ELECTRIFICATION

The problem of affording a supply of electricity to many rural districts is one of economics. In many cases, the loads to be expected are very low and the returns, correspondingly small, demand that expenditure must be kept at a minimum. In a number of locations, the demand can be met by a small pole mounting transformer for which the control switchgear can be simple air-break switches, fuses, switch-fuses, or pole-mounting circuit-breakers. The remoteness of equipment of this type to the source of supply is generally such that breaking capacity is not of major importance. Switchgear capable of clearing faults of 50 or 75 MVA at 6·6 or 11 kV is quite adequate for the majority of applications.

In other locations, larger loads are connected as for example where a factory exists in a rural district. Here the requirements may be as high as 300 or 400 kVA and to meet this the weatherproof sheet steel kiosk is a convenient form, either as a point for direct distribution to the consumer at service pressures, or as a main switching point for the control of spur lines to other centres where pole mounting equipment as described may be installed. A kiosk is suitable also for housing h.v. switchgear of a higher breaking capacity than that of fuses or pole mounting circuit-breakers.

The horn-break switch, either with or without fuses, is a simple form of control and is available in a variety of types, *e.g.*, horizontal or vertical. The least expensive is the single-pole vertical type, operated by means of a pole from ground level. This is not always a convenient method and the majority of switches are of the triple-pole type with an operating mechanism at ground level which operates all three phases.

Examples of this type are shown in Fig. 25-1 and Fig. 25-2, these being on the primary network. For secondary distribution a simple rotary blade design permits a compact vertical switch with separate line insulators as shown in Fig. 25-3.

By far the most popular switchgear for controlling small outdoor transformers is the fuse. It is cheap and the cost of replacement elements is very low. In one type, the blowing of a fuse element automatically releases the retaining catch allowing the fuse tube to swing down. This effectively isolates the circuit and at the same time gives an immediate indication to a linesman of the blown condition, saving considerable time. The sequence of operations with this type of fuse-switch is shown in Fig. 25-4. Rewiring is done at ground level by lowering the fuse tube in a specially designed pole-head as shown at (C) in Fig. 25-4.

In this design, too, it is possible to isolate a healthy line by releasing the fuse tube with the pole, the fuse-switch functioning exactly similar to a pole-operated isolator. By replacing the fuse tube by a copper tube the unit can be used as a plain isolator. This design is available for voltages from 660 to 33,000 volts and elements are available from 0·5 amperes to 100 amperes. Examples of fuses in use on pole substations are shown in Figs. 25-5 and 25-6.

FIG. 25-1.—*Horn Break Switch on H Mast, with ground level operation. Note horn gap arresters.*

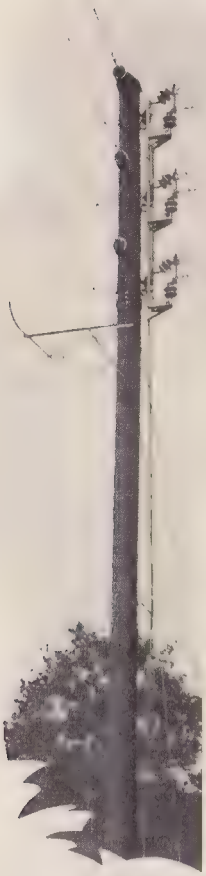


FIG. 25-2.—*11 kV Vertical type Horn Break Switch.*

FIG. 25-3.—*660 volt Air Break Switch with rotary type blades and separate line insulators.*

FIG. 25-4.—*Operation Sequence of type "D" Fuse-Switches (J. & P. Ltd.).*

(*a*) *Fuse intact. Fuse tube locked until fuse element blows or tube is manually released.*

(*b*) *Fuse blown. Fuse tube automatically released, swings down, completely opening the circuit and giving indication to linesman.*

(*c*) *The fuse tube being removed for rewiring at ground level.*

(*d*) *Re-closing after rewiring.*

FIG. 25-5.—*Typical Pole-mounting Transforming Stations, with fuse protection.*

FIG. 25-6.—*Typical Pole Substation with "D" Fuse-switches.*

By far the majority of faults on overhead lines are of a transient nature, due to lightning, birds, branches of trees, etc. These are, in general, self-clearing, but they cause fuse operation. A simple repeater switch has been produced which, when fitted to a fuse-switch, is automatically released to close the circuit via a second fuse-switch, the operation being initiated by the first fuse tube swinging down. The time interval between initial blowing and the second fuse coming in is about 0·4 seconds.

If a time delay of longer duration is required, the repeater switch is fitted with a mechanical time lag adjustable between one and fourteen seconds approximately. A typical assembly with repeater switch is shown in Fig. 25-7 where the first fuse-switch (remote) has operated and swung down, and the repeater switch has closed to bring into service the second fuse-switch (near). The arrangement, although requiring two fuse-switches per line plus the repeater switch, does, on remote rural lines, save considerable time, and in perhaps 95 per cent. of faults, restores supply within a few seconds.

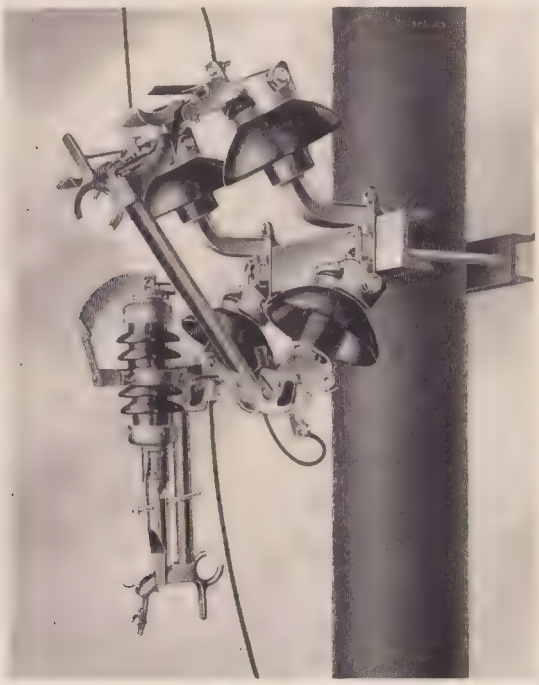


FIG. 25-7.—*Repeater Switch, in closed position, with duplicate fuse-switches* (*J. & P. Ltd.*).

Fuses may be used also for line protection. In this case it is often found that series applications occur and the problem of discrimination arises. In the event of a fault, all fuses in series up to the point of fault carry the current, but it is required that only the fuse *nearest* the fault should blow. During the period of time necessary for the " clearing " fuse to completely isolate the fault, those fuses nearer the point of supply and further away

from the fault will be carrying the current and heating up. It is essential that this process be insufficient to cause deterioration in the elements. Therefore, based on the known value of fault current the fuses must be chosen so that they are not affected by through currents.

This choice is made by reference to data which not only gives melting times (the usual times given in makers' fuse curves) but also the arcing times. These two times added together are known as the total clearance times. Given such curves, fuses in series should be chosen such that a difference exists between the *total clearance* time of the fuse nearest the point of fault and the *melting* time of the fuse adjacent but nearer the supply point of, say 0·4 seconds (this will vary with makes of fuse).

This is explained in Fig. 25-8 : If we assume that fuse C has a 5 ampere rating, we find from curves that, with a fault current of 200 amps., the total clearance time is 0.105 seconds. Add to this 0.4 seconds giving 0.505, and reading from the curves at this time and for 200 amperes fault, the fuse B must have a rating of 20 amperes.

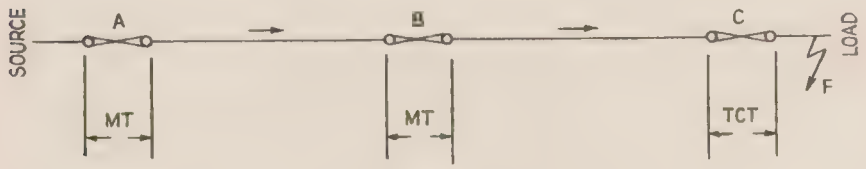


FIG. 25-8.

TCT = TOTAL CLEARANCE TIME
MT = MELTING TIME
MT FUSE B = TCT FUSE C PLUS 0.4 SEC.
MT FUSE A = TCT FUSE B PLUS 0.4 SEC.
ALL TIMES CALCULATED FOR VALUE OF FAULT CURRENT

A typical set of fuse curves showing both melting and total clearance times is given in Fig. 25-9 where the black curves represent melting times and the red curves the total clearance time. The figures above for fuses C and B are taken from these curves.

If we have a third fuse as at A, then the total clearance time of B (0.65 seconds) must have added to it a further 0.4 seconds, giving 1.05 seconds as the melting time of fuse A, and reading from Fig. 25-9 for this time and 200 amps. through fault, we find the rating must be 30 amperes.

Where the load to be supplied is larger than that normally supplied by pole mounting transformers, the kiosk substation is ideal. It is reasonably transportable so that if the load should increase beyond the capacity of the kiosk, other arrangements can be made and the kiosk removed to another site more suitable.

The kiosk consists of a steel housing to contain h.v. and l.v. switchgear, and the power transformer, each in a separate compartment with access doors. It is weatherproof against driving rain and snow, and by suitable treatment, can be rendered trouble-free against condensation. The usual treatment is cork spraying on the underside of the roof. This, together with the heat generated within the transformer, and efficient ventilation, has proved very successful.

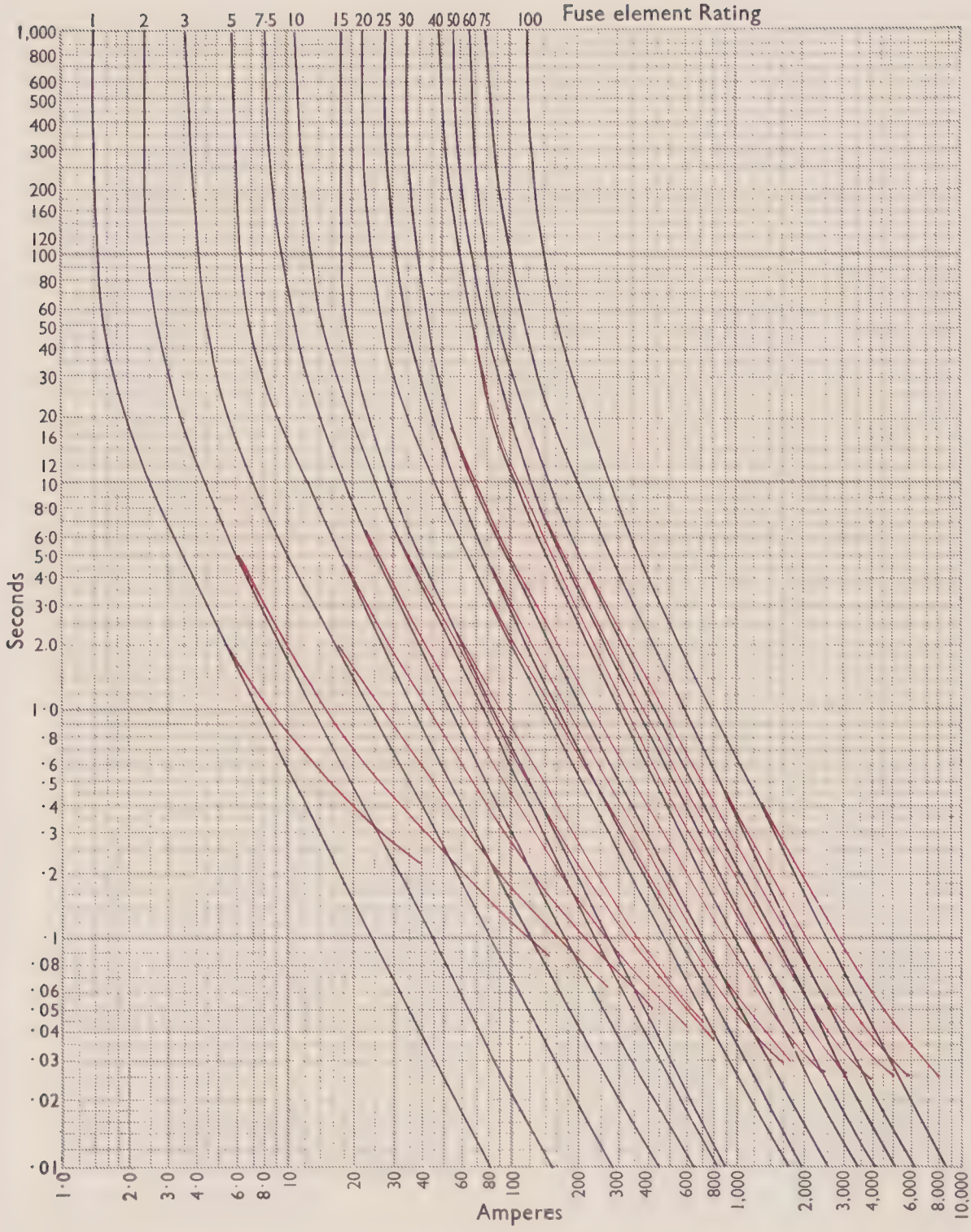


FIG. 25-9.—*Time/current Curves for standard slow-blowing Type F fuse elements.*

A typical exterior view of a kiosk substation is shown in Fig. 25-10, and given a pleasing colour scheme, it can harmonise successfully with its surroundings and is not an eyesore in residential districts.

The type of switchgear can be one of many. For the h.v. side, the cubicle type is most economical but metalclad gear can equally well be installed. Examples of these types are shown in Figs. 25-11 and 25-12. On

FIG. 25-10.—*External view of Kiosk Substation.*

the l.v. side, general practice is to fit tailless fuse units or skeleton type gear as described in Chapter VI. This is cheap and takes up very little space, as Fig. 25-13 will indicate. Many kiosks have been built with circuit-breakers on the l.v. side but this increases the size of the kiosk considerably.

For loads between those suitable for fuse control, and those demanding a kiosk, the pole-mounting circuit-breaker is ideal. This is designed generally on the lines of indoor circuit-breakers except that it has terminal

arrangements suitable for its application. A typical circuit-breaker is shown in Fig. 25-14, with bushings for both incoming and outgoing leads. Other arrangements allow for cable boxes on either side or for a trunking to a transformer. In the latter case the breaker and transformer are ground mounted.

For the reasons stated earlier, automatic reclosing is a desirable feature and can be arranged with this type of circuit-breaker.

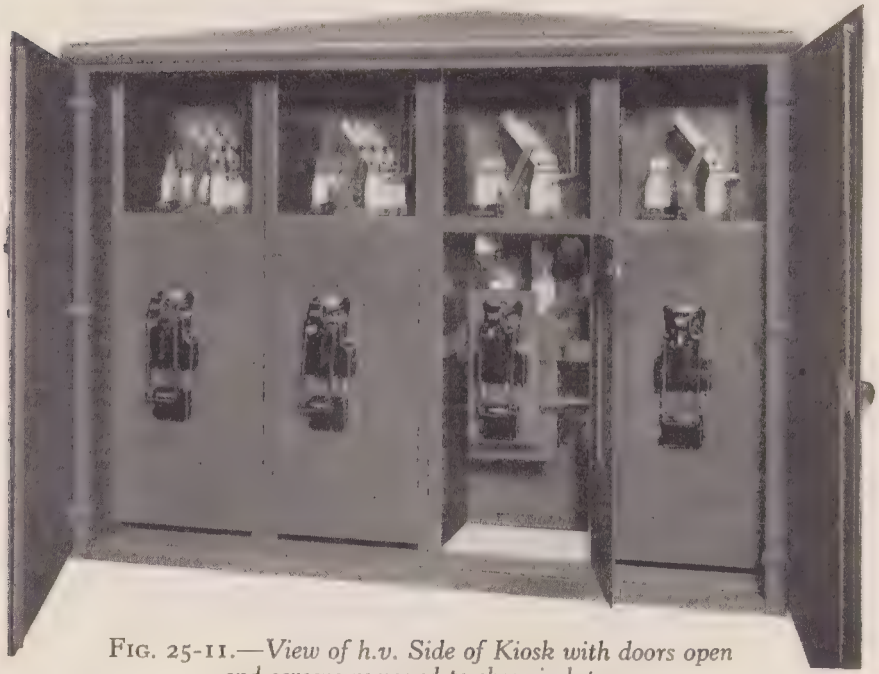


FIG. 25-11.—*View of h.v. Side of Kiosk with doors open and screens removed to show isolators.*

The use of series overload trips is usual, eliminating the need for current transformers. In the design illustrated, a single-break is employed with an arc control device of the side baffle type (see Chapter VIII).

An outdoor metering equipment for pole mounting is shown in Fig. 25-15.

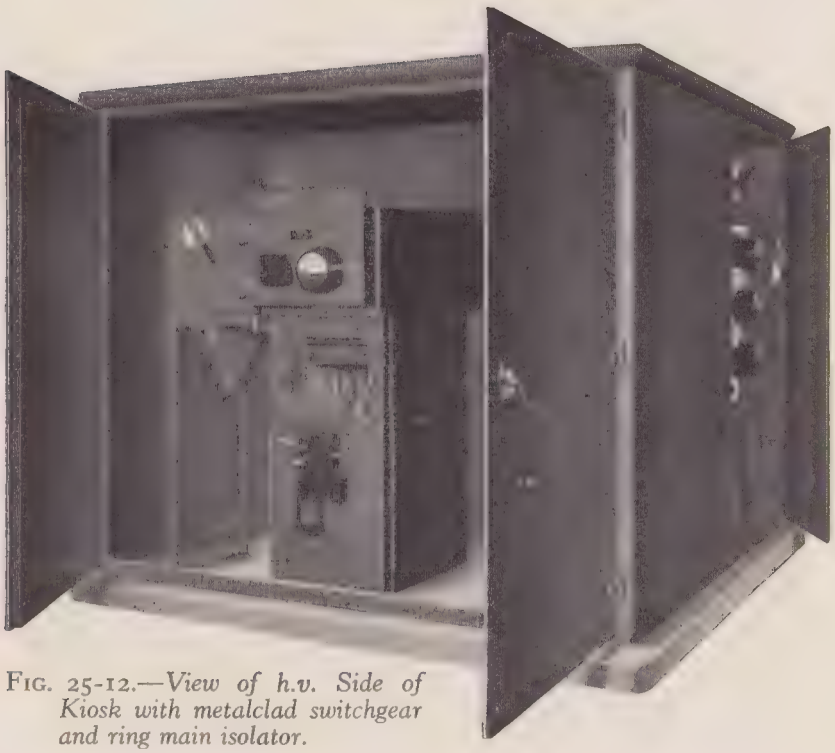


FIG. 25-12.—*View of h.v. Side of Kiosk with metalclad switchgear and ring main isolator.*

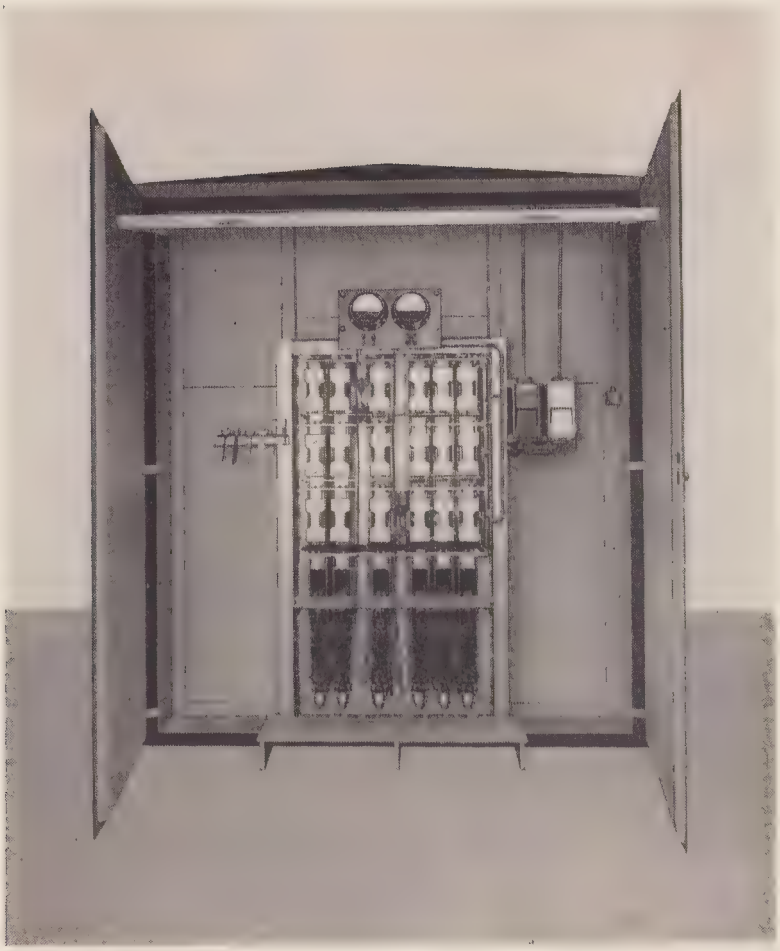


FIG. 25-13.—*View of l.v. Side of Kiosk. Note insulated operating platform.*

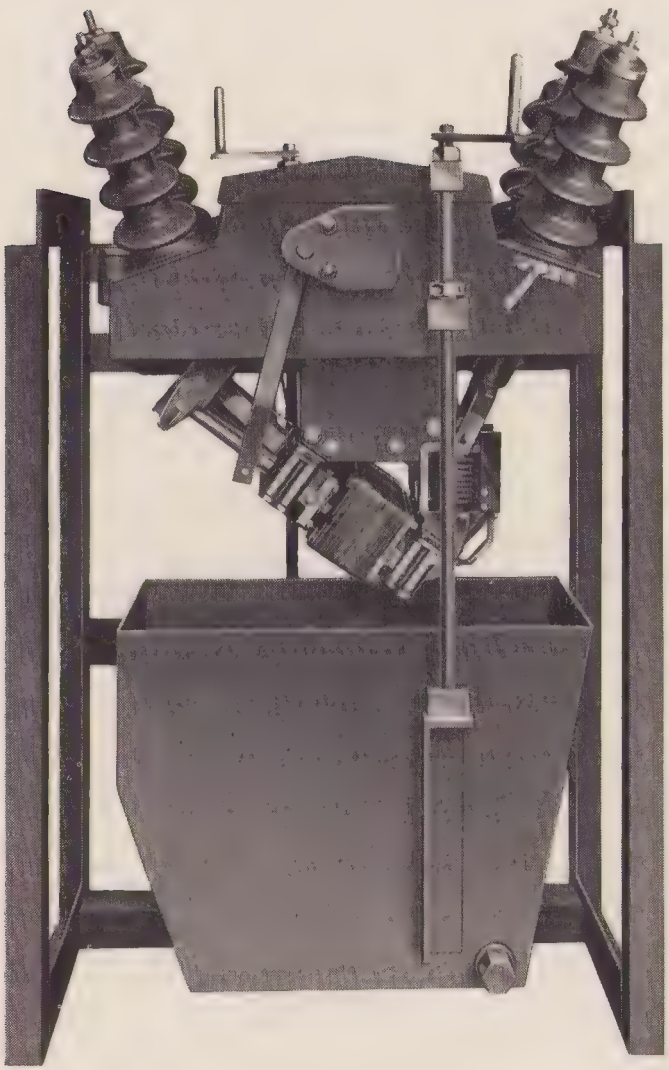


FIG. 25-14.—*Outdoor Pole Mounting Circuit-Breaker (J. & P. Ltd.).*

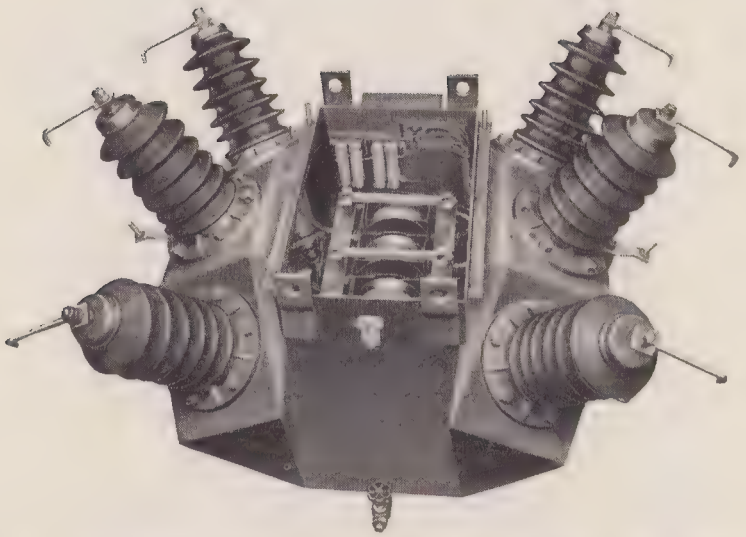


FIG. 25-15.—*Outdoor Metering Equipment, self-contained with voltage and current transformers, oil-immersed. Suitable for 33 kV service and for pole platform mounting to meter tapped supply to consumer (J. & P. Ltd.).*

CHAPTER XXVI

MISCELLANEOUS EQUIPMENT

Panel Materials.

The choice of materials for panel type switchboards or control panels lies between steel or Sindanyo. The latter is a manufactured material and is now generally preferred to slate or marble. The latter material is now practically obsolete. Slate, though still in use to a small extent, suffers from the possibility of hidden metallic conducting veins. For this reason, all panel fixing bolts and instrument stems which pass through the panel are insulated by bushing. It is because of these defects that Sindanyo has become so popular. As indicated, this is a manufactured material and is an asbestos-base synthetic phenol production and complies with B.S. 737 for self-extinguishing boards. It is available in a variety of finishes, the standard for switchboard work being black enamel. It has a very high insulation resistance and dielectric strength. Mechanically it is excellent and thinner panels may be used than would be necessary in slate.

There can be no possibility of metallic veins so that the need for bushing disappears. It is easy to drill and machine and is non-hygroscopic and unaffected by temperature. It is a suitable material for shipment abroad by reason of the foregoing and the reduced weights. The dielectric strength of Sindanyo is given in Fig. 26-1.

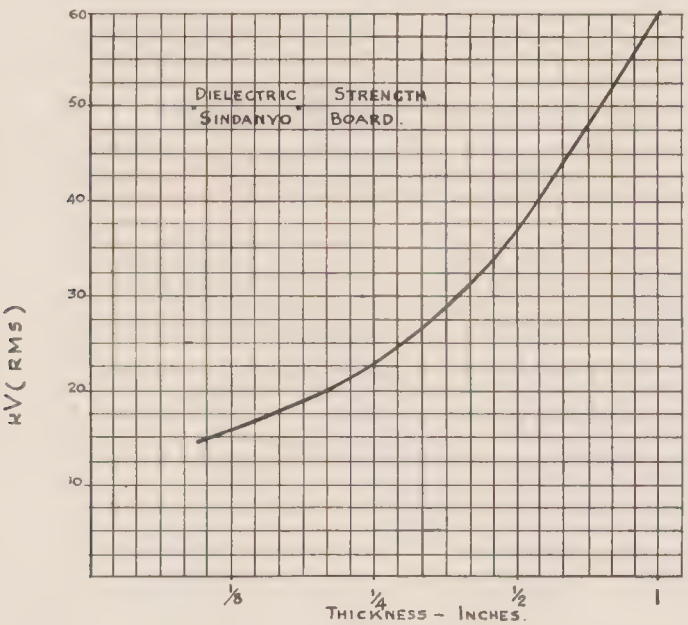


Fig. 26-1.—*Curve showing dielectric strength of Sindanyo (Turners Asbestos Cement Co., Ltd.).*

Panel Frameworks.

Usually of angles and flat iron, or of pipe. The former involves the drilling of many holes, each accurately placed. When pipes are used, all supports are clamped to the pipes, in the manner of builders' scaffolding, thus avoiding all drilling. This makes for easy adjustment and any small error can be quickly remedied.

Panel frameworks must be bonded together by an earth bar of adequate section, which in turn must be connected to the general earthing system.

Panel Wiring.

In all switchboard or control board wiring, it is important that it be run in a neat, orderly fashion, following the circuit wiring diagram closely, both electrically and, as far as possible, physically. This enables checking and testing to be carried out easily, particularly on complicated circuits. The terminations of each wire should carry a numbered ferrule, the numbering being determined by the designer and stated on his diagram.

The colouring of wiring should follow the established standard and where possible, current and voltage wiring should be segregated.

For many years, V.I.R. cables have been used for switchboard and panel wiring. The war 1939/1945, bringing in its train the great need for conserving supplies of rubber, led to the almost complete use of P.V.C. cables. These in many respects are excellent for this purpose, particularly in their flameproof and oil resisting properties.

Unfortunately, they have a very low insulation resistance value, and in the ordinary grades, are not suitable for the extremes of temperature.

The most popular conductors are 7/.029, 3/.029 and 1/.083. The danger with a single strand connection is a break in it, a danger not existing to the same degree in a multi-strand. For wiring across hinged panels, the use of single wires in a flexible metallic tube, or a built up multi-core cable, are both popular. It is essential that these flexibles be adequately anchored on both fixed and moving parts to avoid strain on the terminals.

In order that the wiring may maintain its original layout, it must be cleated in position, this usually being achieved with simple metallic stirrups which are enamelled.

Circuit Fuses.

Fuses should be located as nearly as possible at the source of supply and wherever possible be of the front-of-board type, accessible for replacement or rewiring without access to chambers which may contain "live" circuits. A variety of fuses is available, two popular types being the cartridge type, and the type with the trade name "Slydlok."

The latter have not a high breaking capacity and it is important to watch that on low voltage switchgear, particularly where fault values of 25 and 30 MVA may arise, the circuit fuses which are directly connected to the main circuit have equal breaking capacity. It is very desirable that all fuses be clearly labelled for recognition. Any special purpose fuses, or fuse holders with links (as in trip circuits), may with advantage have distinctively coloured holders.

Indicating Devices.

The use of lamps for the purpose of indicating circuit-breaker and/or isolating switch positions (open or closed) is general on most control boards

and often on direct controlled switchgear. They demand the use of a separate source of supply, usually D.C. and failure of this or a lamp burn-out may lead to confusion. In order to give long life, it is usual to select lamps suitable for a voltage twice that of the actual supply. This reduces the illumination but ample indication is obtained nevertheless. Where vibration and shock is possible, as where lamps are subject to the shock of a circuit-breaker opening, traction type lamps are used. The older type of indicating lamp projecting some inches in front of the panel is now a thing of the past and much ingenuity has been shown in designing lamp fittings which are almost flush with the panel front and yet give indication to an observer standing at a point not directly in front of any particular panel.

These fittings, too, are arranged so that a lamp may be removed and replaced from the front. Instead of glass lenses, Perspex has been used with success, although this is prone to scratching and occasionally is affected by heat if the lamp is close up.

Red and green are the accepted colours to indicate the "on" and " off " position of the major apparatus, following the usual " red for danger " and " green for all clear " convention.

Where protective gear is fitted, it is often desirable to indicate that its functioning has caused the circuit-breaker to trip out, as opposed to deliberate circuit disconnection by the operator, and a white lamp is used for this purpose, wired in the protective gear circuit

Whether lamps are fitted or not, mechanical " on " and " off " indicators are general on circuit-breakers and isolating switches. These suffer one disadvantage, that of not being so readily observable at a distance.

CABLE TERMINATIONS.

One of the most important features of switchgear design is that of providing adequate facility for making of cables, whether main or auxiliary. The user of switchgear can help in this direction by an intelligent layout of ducts and trenches and of ample depth. It is in the nature of many switchgear designs that the cable termination is near to floor level. Economics dictate this generally. This must be borne in mind in designing trenches. Many switchgear designs to-day, in the demand for saving space, are arranged for cables to be made off from the front of the switchgear unit. Care should be taken that this can be reasonably performed without acrobatics. Particular care should be paid to the provisions for compound filling.

It is rare that a standard line of cable boxes made for general purposes is entirely suitable for switchgear and by far the most satisfactory designs are those which are made to suit the switchgear and not vice-versa. Fabricated boxes instead of cast are usual on the higher voltages and in metalclad switchgear.

It is important to watch when a standard cable box is used that the specified clearances for switchgear are not undermined by those on the cable box itself.

FINISHES.

Black glossy panels, when these are in slate or Sindanyo, are the general rule.

When using steel panels—a general practice on the modern remote control board—a light matt grey is very pleasing, the panel often set off by a surrounding beading in black enamel.

Instrument and relay cases are now usually all black instead of the earlier style where the edges were nickel or chrome plated. The latter gives a little relief on an all black board but if not looked after, soon discolours.

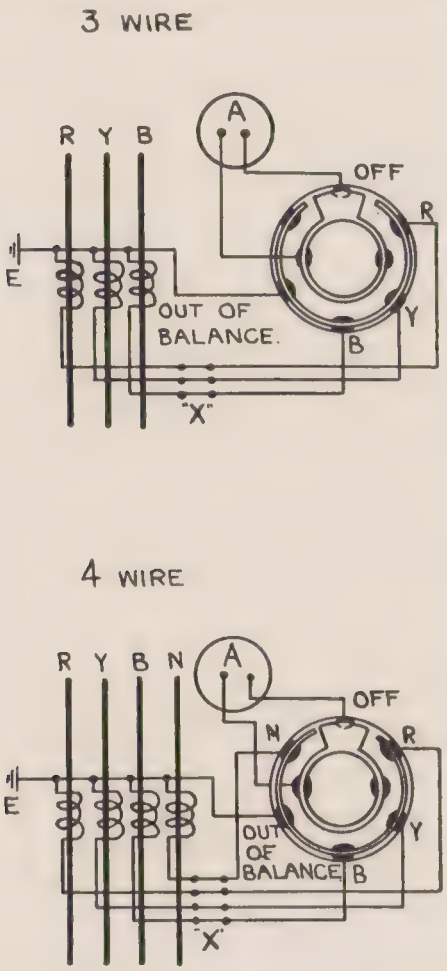


FIG. 26-2.—*Typical Connection Diagrams for Ammeter Switches (other instruments connected at "X").*

Switch units proper may be finished in any colour but the most popular is grey or green. Certain types of metalclad switchgear are given an air of lightness by using these colours while the opposite is the case when finished black.

INSTRUMENT SWITCHES.

For the purpose of obtaining current readings in the different phases, or voltage readings across them, rotary type switches are supplied in a variety of forms. They are of the back-of-board type and except in the

cheapest forms, are of moulded construction. Typical connection diagrams for both ammeter and voltmeter switches are given in Figs. 26-2 and 26.3.

Synchronising Switches or Plugs.

A scheme of synchronising by means of interlocked control switches has been given in Chapter XV. These control switches, of the controller

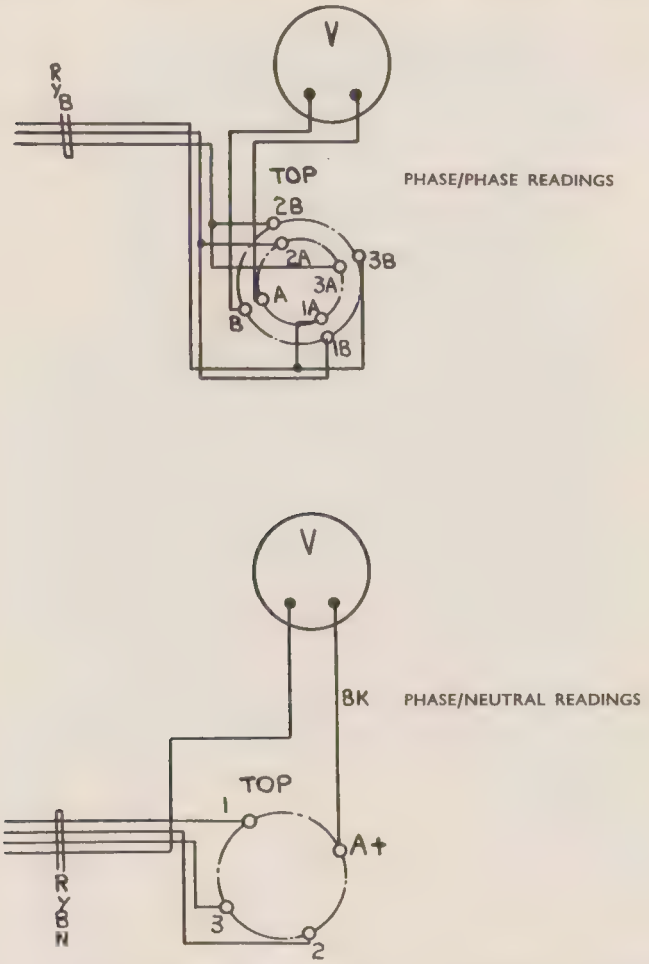


Fig. 26-3.—*Typical Connection Diagrams for Voltmeter Switches.*

pattern, are similar in design to a circuit-breaker control switch. Diagrams for synchronising by means of plugs and sockets are given in Appendix D. These plugs and sockets follow the design of house service plugs and sockets but on a larger scale, and are arranged so that the plug must be inserted in a correct way.

Tripping Batteries.

An essential feature of modern protective systems using relays, as described in Chapter XX, is a tripping battery to give supply to the trip coil

after the relay has operated. Such a battery will give a supply at, say 30 or perhaps 24 volts, and will be completely self-contained with charging equipment, rectifier for connection to an A.C. supply, and with test and indicating equipment. A typical unit is shown in Fig. 26-4 while Fig. 26-5 is a diagram of connections for the equipment.

FIG. 26-4.—*Tripping Battery, with Charger and Test Equipment (Nife Batteries, Ltd.).*

The unit is arranged for :—

(*a*) Trickle charge.
(*b*) Quick charge.
(*c*) Charge " off."

the control being by one master switch.

The test equipment comprises an ammeter, resistance and a retractive switch connected in series across the battery. The value of the resistance is such that a fully charged battery will pass a test current equal to one half

the rated capacity of the battery. The use of an ammeter is preferable to a voltmeter as it ensures that a test current is definitely passing. A blue line mark on the ammeter indicates the fully charged state while a red line indicates the need for recharging.

The use of nickel cadmium alkaline batteries is now general and the following schedule indicates the range available.

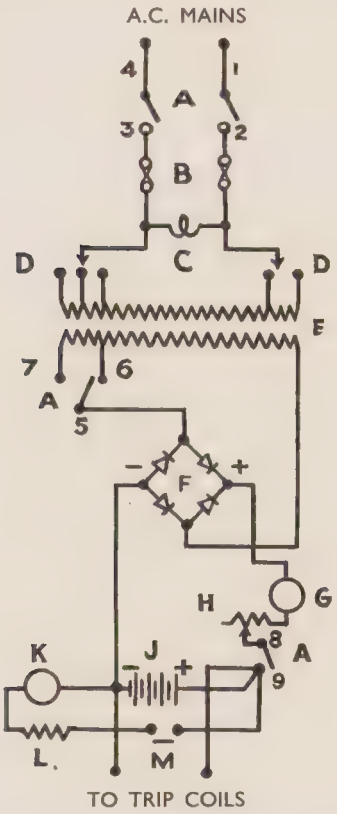


FIG. 26-5.—*Diagram of Connections of Tripping Battery with Charger (Nife Batteries, Ltd.).*

Ampere Hour Capacity 10 Hour Rate	CHARGE		For Trip Circuits of Amps.
	Trickle Milli-Amps.	Quick Amps.	
5	17	0·2	15
10	33	0·2	30
15	50	0·3	45
25	85	0·5	75

CHAPTER XXVII

AIR-BREAK FLAMEPROOF SWITCHGEAR

THE extent to which electricity is now in use underground in Great Britain may be judged by the fact that, whereas in 1912 the total h.p. of motors was 317,000 the latest quoted figure is 1,581,646 as at 30th June, 1948. This total is made up as follows :—

Duty	No. of Motors	Horse-power
Haulage	10,474	551,523
Pumping	9,709	481,670
Air Compressing	848	35,878
Coal Cutting	6,004	250,613
Conveying and Loading	11,004	203,327
Other Portable Machines	5,203	24,592
Auxiliary Ventilation	2,042	20,454
Miscellaneous	1,679	13,589
Totals	46,963	1,581,646

These figures reflect the degree of safety now achieved in the design of electrical apparatus for use underground without which progress would have been impossible.

That there is a high degree of safety is due to the co-operative research and development by many bodies into the technique of rendering electrical apparatus flameproof to the stringent requirements of legislation covering the use of electricity in mines. These bodies include the Mining Department of the University of Sheffield, the Safety in Mines Research Board, the Ministry of Fuel and Power, the Electrical Research Association, together with manufacturers and users.

It can be claimed, as a result, that British apparatus is second to none for use in any industry where explosive atmospheres exist, and, coal mining apart, the apparatus is used in gas works, oil refineries, grain silos, chemical works, and others.

The problem of making electrical apparatus "flameproof" has been admirably summed up by H.M. Chief Inspector of Mines in his preface to the publication "A Review of Flameproof Testing" issued by H.M.

Stationery Office. In this preface, it is pointed out that in coal mining the first line of defence against explosion of inflammable gas is, and always has been, adequate ventilation. Reasons are given why, in spite of precautions, this is not a perfect safeguard, and it is therefore necessary to take a variety of steps to safeguard against or to eliminate potential sources of ignition. Thus the safety lamp has been introduced, "permitted" and "sheathed" explosives have been developed, and "flameproof" apparatus designed and made.

Because of the "breathing" which results from changes of temperature and the consequent expansion and contraction of the atmosphere within the enclosure when the apparatus is alternately at work and idle, it is impracticable to prevent an external inflammable atmosphere from entering the enclosure and, having entered, ignition is likely due to arcing at contacts and other causes. To be "flameproof" then, an apparatus must be such that with ignition within the enclosure the flame will not be communicated to the external atmosphere.

The principles of construction of apparatus to satisfy this condition are enumerated in BS.229, a standard produced as a direct result of the work of the authorities named earlier and of manufacturers.

Briefly, a flameproof enclosure must be such that (a) it is not destroyed or distorted by the pressure of the internal explosion (the pressures experienced do not, in general, exceed 100 lbs. per sq. in.) and (b) any openings must be such that flame cannot be propagated through them. The first requirement demands either the use of heavy plate welded to form a suitable housing (as noted in illustrations later), with welding of the highest order, or a cast structure of ample strength, while the second is satisfied by the use of flanged covers, doors, etc., where the width of flange and the gap between marrying faces is within prescribed limits. These limits of gap also apply to shaft glands, determined as a result of research. The use of jointing material such as rubber or asbestos is not permitted.

Apparatus complying with these and other requirements must be certified as flameproof, certification being granted today by the Mines Department Testing Station at Buxton on the conclusion of satisfactory tests at the station. Apparatus so certified must carry an indication of the certificate number, the group of gases for which certified, and the now famous registered mark FLP granted under licence to the manufacturer.

Reference has been made to groups of gases. These are four in number and Table 1 opposite enumerates them and gives details of the maximum gap between joint surfaces etc.

TABLE 1.

Group	Gas or Vapour	Max. Gap between joint surfaces or diametral clearance for operating rods or shafts for apparatus containing air	Breadth of flange joints or length of hole for operating rods or spindles
I	Methane (Firedamp)	·020 inches	1 inch width of flange except in the case of very small boxes, where it may be ¼ inch. 1 inch length of hole for rod or spindle.
II	Blast-furnace gas Hydrocarbons Carbohydrates	·016 inches	
III	Coal gas and coke oven gas Ethylene oxide	0·008 inches between surfaces 0·016 inches clearance for rods or shafts.	
IV	Acetylene Carbon di-sulphide Hydrogen Water gas Ethyl nitrate	Too small to be practicable to justify certification on the basis of a type test	

In certain apparatus, the amount of power necessary for normal working is very small and it is possible to provide circuits in which the power that flows into a short-circuit or earth fault on the apparatus is so small that it is insufficient to ignite an explosive atmosphere. Such apparatus includes bells, signalling gear, control and interlock circuits on heavier gear, etc., and when the conditions outlined are achieved, the circuit is designated "intrinsically safe," indicating that it can be used in places where there is a risk of explosion which cannot be met by the safeguard of flameproof enclosure. Such circuits usually are at very low voltage, e.g. 15 or 30 volts and even 7·5 volts, while the limiting value of short-circuit current is of the order of 1·6 amperes. The source of power such as transformers, batteries, or magnetos must have a high internal impedance and inductive parts of the circuit must be shunted by resistors, capacitors or rectifiers to absorb the power released by the collapse of the magnetic field on current interruption. Any apparatus designed to be "intrinsically safe," must be proved by test to comply with B.S.1259 and a certificate obtained.

The demand for electrical power underground is, in the main, for pumps, road haulages, face and trunk conveyors, coal face machinery such as cutters, loaders, drills, etc., and lighting. The majority of these items are

at medium voltage and because of restrictions as to the amount of oil which is permitted in apparatus within a specified distance of the coal face, the apparatus is of the air-break type.

This is the type of gear to be described in the present chapter and will cover distribution and control gear for use on systems up to 650 volts.

In Fig. 27-1 is shown an air-break circuit-breaker panel primarily designed as a section switch for the control of electrical sections of equipment.

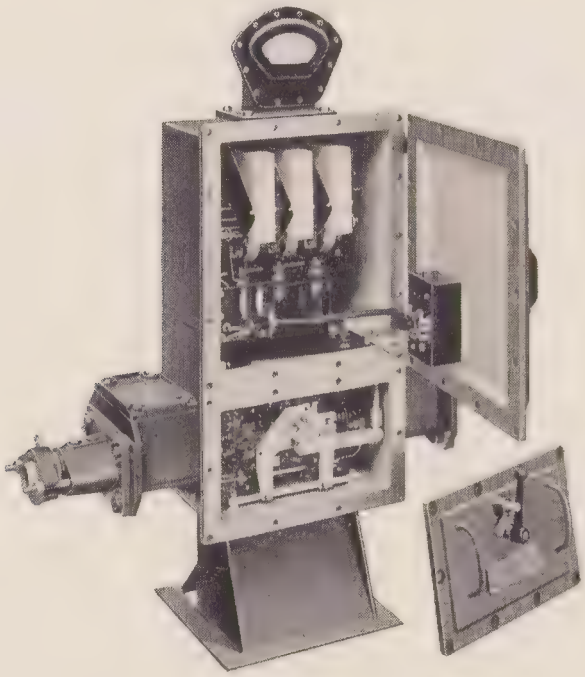


FIG. 27-1.—*Hand Operated Circuit-Breaker*
(The Belmos Company, Ltd.).

It is also used as a hand-operated gate-end box, as shown in Fig. 27-2, when it is fitted with a BS plug and socket electrically interlocked with the circuit-breaker. As is seen, the circuit-breaker is hand-operated, with free handle operating mechanism. Splitter type arc-chutes are fitted to assist effectively in interrupting the arc on fault clearance. Protective devices include overcurrent, earth fault, and under-voltage, the former being fitted with two-rate oil dashpots. The earth fault relay is fitted behind the door of the circuit-breaker chamber and a flag indicator is seen through a small window after operation. Means are provided for hand resetting of the relay and tripping may be checked by means of a test switch.

In a separate chamber below the circuit-breaker is mounted a three-pole isolating switch as shown in Fig. 27-3 which carries a section of busbars for connection to the incoming and/or throughgoing cables or to busbars of adjacent units. The isolating switch is mechanically interlocked with the circuit-breaker and with the cover of the compartment, the interlock being internal, thus preventing unauthorised interference.

In the design used as a gate-end box, an intrinsically safe pilot interlock circuit is provided, the trailing cable to the motor being of the 5-core type

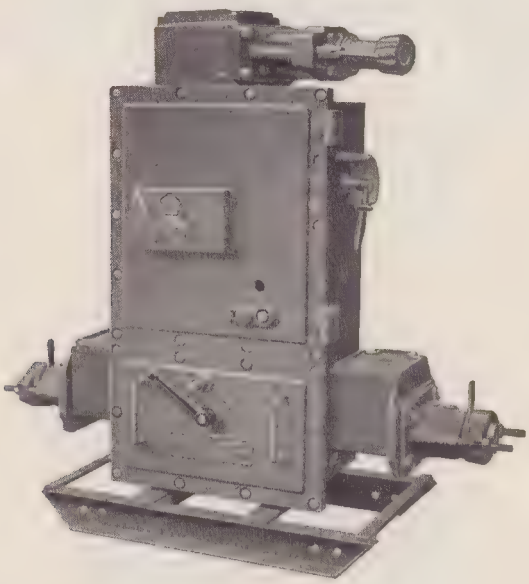


FIG. 27-2.—*Hand Operated Gate-End Box*
(*The Belmos Company, Ltd.*).

with 3 power cores, a pilot core and an earth return core. With this arrangement, the circuit-breaker cannot be closed until the plugs are in position, and withdrawal of the plugs or a break in the pilot or earth core automatically trips the circuit-breaker. This gate-end box is for use generally at the coal face for the control of coal cutters, conveyors, etc., and being hand-operated, is not suitable for remote control. The latter is now a common requirement in mining practice and the automatic gate-end box described later is therefore more popular.

The requirement of the Coal Mines Act which demands automatic protection of a branch cable where the current carrying capacity is less than the main or sub-main from which it is derived, can be met either with the circuit-breaker unit in Fig. 27-1 or by an air-break switch and fuse

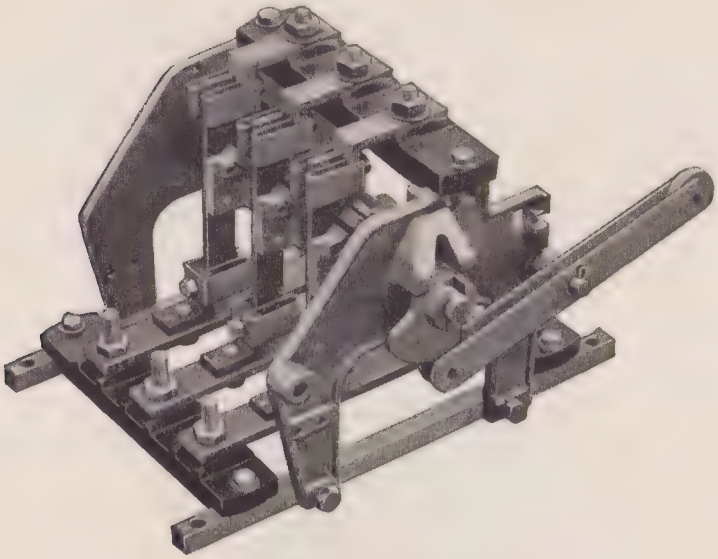


FIG. 27-3.—*Isolating Switch Unit.*

panel as shown in Fig. 27-4, the former being recommended for situations where frequent fuse renewal is likely. This switch fuse unit carries an isolator of the type described earlier and, in the upper compartment, fuses of the rewireable or of the H.R.C. type as preferred.

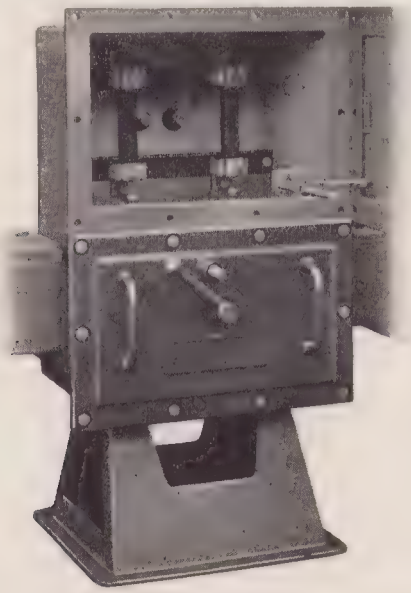


FIG. 27-4.—*Air-Break Switch and Fuse "Tee-off" Panel (The Belmos Company, Ltd.).*

A unit which has been designed to fulfil almost all requirements for a contactor unit which are encountered in mining and other industries, is shown in Fig. 27-5. This unit, in its simplest form, with overcurrent protection and cable sealing boxes for armoured cable, provides for "direct-on" starting and control of pumps, haulers, and similar apparatus.

Fitted with an outgoing BS plug and socket, earth fault protection, and intrinsically safe low voltage pilot circuit, the unit becomes an automatic gate-end box suitable for the remote control of coal face machinery.

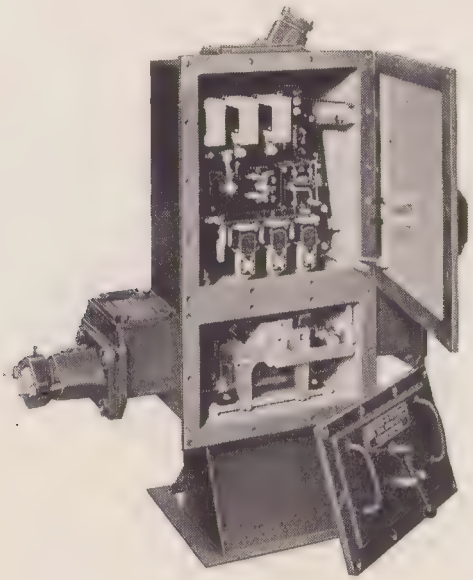


FIG. 27-5.—*Air-Break "Direct-On" Contactor Starter or Gate-End Box (The Belmos Company, Ltd.).*

Among other things, the Reid Report (Mechanisation Advisory Committee to the Ministry of Fuel and Power) called attention to the fact that "the provision of lightweight switchgear of simplified design for use at the coal face is a matter of urgent necessity."

The gate-end box shown at Fig. 27-5 weighs approximately 5 cwts. and in its simplest form on skids, and without ammeter, measures an overall height of just over 3 feet. Space and ease of transportation with the advance of the coal face make such a unit a little difficult to handle and to meet the demand quoted above, a gate-end box weighing $3\frac{1}{2}$ cwts. and having an overall height of only 23 inches has been developed. This unit is shown

in Fig. 27-6 and it will be noted that the low height, and in consequence the reduction in weight, has been achieved by a radical re-disposition of the apparatus. For example, the contactor unit is arranged with the magnet on the front face of the panel and is linked to the contactor proper which is on the rear face of the panel.

The isolating switch (of the reversing type) has been accommodated at the rear of the unit but is operated from the front. As in all contactor units described in this chapter, the panel is arranged to swing forward, thus providing for easy inspection and maintenance. As in the earlier

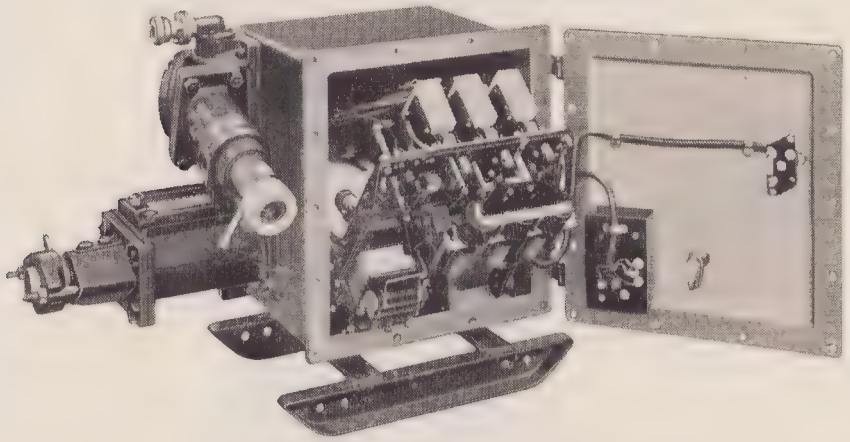
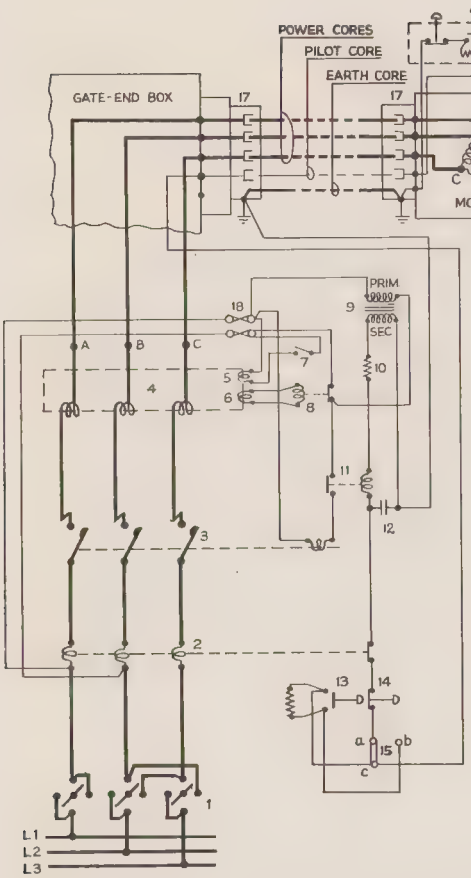


FIG. 27-6.—*Dwarf-Type Air-Break Automatic Contactor Gate-End Box (The Belmos Company, Ltd.).*

type of gate-end box, this "dwarf" unit is fitted with overcurrent and earth fault protection and is arranged for intrinsically safe low voltage remote control. Fig. 27-7 is a diagram of connections for this unit.

Designed to line up with the "dwarf" gate-end box, and developed for similar reasons, is the drill unit shown in Fig. 27-8. This unit is for the control of one 50 cycle drill, $1\frac{1}{2}$ h.p. at 125 volts and the housing, which is similar to that of the gate-end box, accommodates an isolating switch, a 1·5 kVA three phase transformer (tapped on the primary side to suit primary voltages of 440, 500, 550, and 625 volts), primary H.R.C. fuses, secondary contactor, with over-current (stalling) and earth fault protection, and low voltage intrinsically safe remote control. Owing to the weight of the transformer, the interior of this unit is not made to swing forward but is arranged to be drawn out on slides.



1. REVERSING ISOLATOR
2. OVERCURRENT RELEASES.
3. CONTACTOR
4. CORE BALANCE CURRENT TRANSFORMER
5. TEST WINDING
6. SECONDARY WINDING
7. TEST SWITCH
8. EARTH FAULT RELAY
9. VOLTAGE TRANSFORMER 15V SECONDARY
10. LIMITING RESISTANCE
11. CONTROL RELAY
12. CAPACITOR
13. LOCAL START BUTTON WITH HOLD-ON RESISTANCE
14. LOCAL STOP BUTTON
15. CHANGE-OVER LINKS FOR LOCAL OR REMOTE CONTROL
16. REMOTE CONTROL STATION AT MOTOR
17. B.S. PLUG AND SOCKET
18. CONTROL CIRCUIT FUSES

Note: For Remote Control with Local Stop—Link a and c at 15.
For Local Control with Remote Stop—Link a and b at 15.

FIG. 27-7.—*Typical Diagram of Connections for Gate-End Box with Intrinsically Safe L.V. Remote Control. Pilot Interrupted at Motor.*

Heavy underground conveyor duty demands the use of slip-ring motors, experience showing that for motors above approximately 50 h.p., this method of starting has distinct advantages, giving longer belt life by reason of the smooth start, especially when starting with heavily loaded belts. The unit shown in Fig. 27-9 is a 3-step stator-rotor starter, fully automatic with variable timing relays, overcurrent protection, and reversing isolator. Local or remote control can be arranged together with sequence control if required.

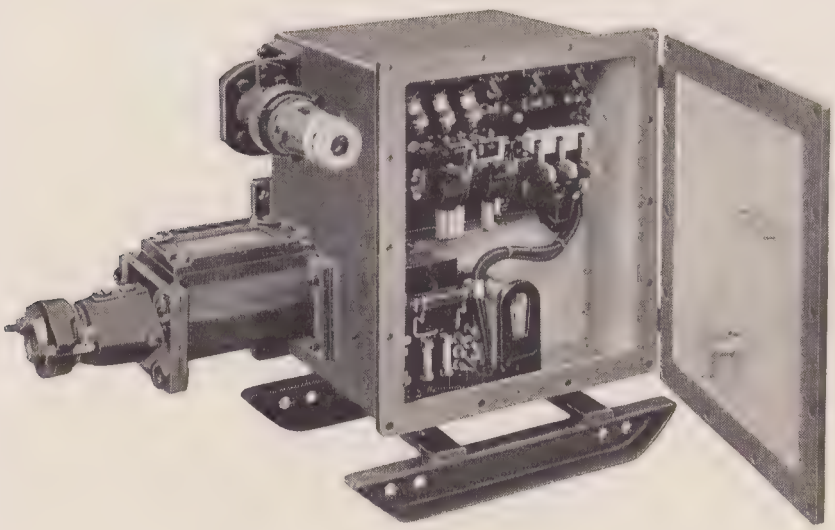


FIG. 27-8.—*Single 50 Cycle Drill Control Unit (The Belmos Company, Ltd.).*

Resistances for the rotor circuit are mounted separately and can be arranged in single, double, or triple unit banks to suit the duty specified. These resistances are of the air-cooled grid type and are housed in specially designed flameproof chambers. A typical double bank resistance unit is shown at Fig. 27-10.

As an alternative to the 3-step rotor starter, for slip-ring motors, a star-delta unit has been developed for use with squirrel cage motors. This unit follows the line of the rotor starter Fig. 27-9, the contactors being re-arranged to provide for star-delta change-over, with suitable mechanical and electrical interlocks.

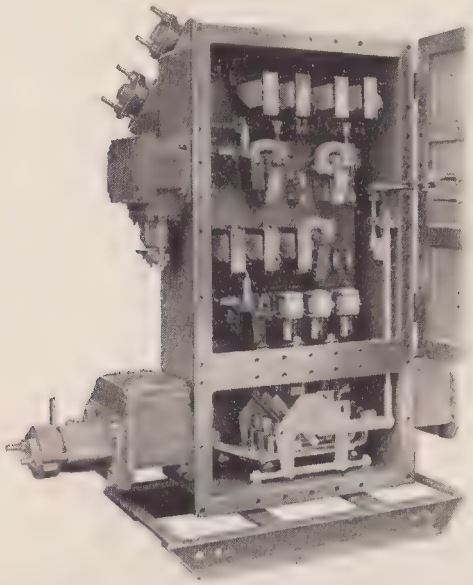


FIG. 27-9.—*3-Step Automatic Stator-Rotor Starter for Slip-Ring Motors (The Belmos Company, Ltd.).*

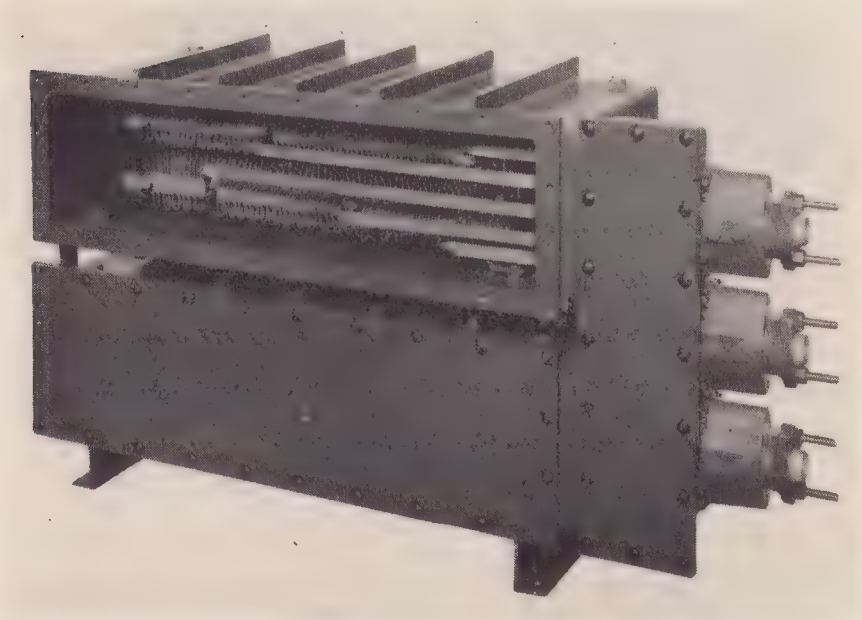


FIG. 27-10.—*Two Tier Flameproof Resistance Unit (The Belmos Company, Ltd.).*

Fig. 27-11 illustrates a self-contained assembly comprising stator contactor, isolator and drum controller, which, in conjunction with the flameproof resistances described earlier, is designed as a control unit for underground haulages. The controller has 7 points forward and reverse and is designed to give long life under the arduous conditions of mining. A double-pole no-volt relay provides an electrical interlock to ensure the return of the controller to the "off" position in the event of a supply failure

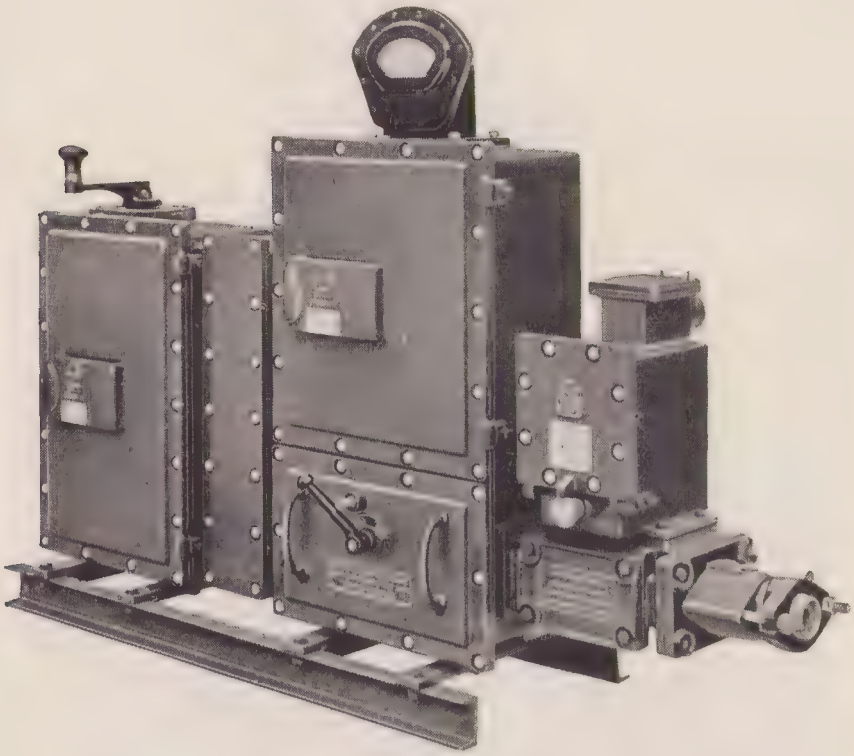


FIG. 27-11.—*Haulage Control Unit with Signalling Transformer on Right (The Belmos Company, Ltd.).*

or in the event of the contactor opening on overload in the intermediate position. The isolating switch is, in this case, interlocked with the doors of both contactor *and* controller chambers. The connecting box between the contactor and controller chambers is arranged to carry stator, rotor, and resistance cable sealing boxes.

For the remote control of automatic contactor units, the flameproof push button switch shown at Fig. 27-12 has been developed. This switch is suitable for control at line voltage, or, when fitted with suitable resistance, for intrinsically safe low voltage control.

No attempt has been made in this chapter to describe the many variations which arise in the manner of switching. Suffice it to say that these include power sequence, pilot sequence, sequence interlocks, starting of conveyors in sequence by means of belt switches, safeguards against belt breakage, and others. All these can be applied to contactor units of the types described herein.

In recent years, more and more attention has been given to the problem of underground lighting, particularly in main roads, haulage houses, sub-stations, etc., and more recently to the coal face itself. Under certain

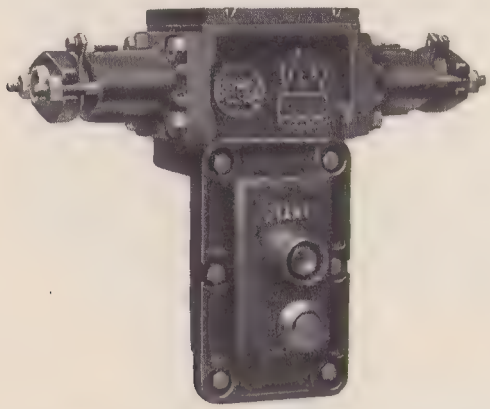


FIG. 27-12.—*Flameproof Remote Stop/Start Station (The Belmos Company, Ltd.).*

conditions, the maximum voltage for lighting may now be 250 volts this being a relaxation of earlier limits. The lighting transformer unit shown in Fig. 27-13 has been developed to allow for this higher voltage, while at the same time it has been arranged so that it can be moved from one pit to another, even in different areas, where the primary voltage may be entirely different. It comprises a main double-pole isolating switch in the lower compartment, with an air-cooled single-phase transformer in the upper compartment. The latter has been provided with multiple tappings which permit connection to *any* primary system voltage in the range 400 to 625 volts, has the secondary winding arranged in two sections for connection in series or parallel to give voltage ranged 220-250 and 110-125 respectively, and is provided with a mistake-proof change-over link for series-parallel selection. The unit is equipped for four outgoing circuits,

each separately fused, and three sizes of transformer are available, namely 1, 2 or 3 kVA. Selection for primary voltage is by means of H.R.C. fuses acting as tapping links, as shown in the diagram Fig. 27-14.

The use of the special change-over link for series-parallel selection ensures that the change-over is complete and it is impossible to make a mistake in re-connection as is the case when three separate links are used, a mistake which might involve the short-circuiting of the two mid-points of the secondary half-windings. It further ensures that when the windings

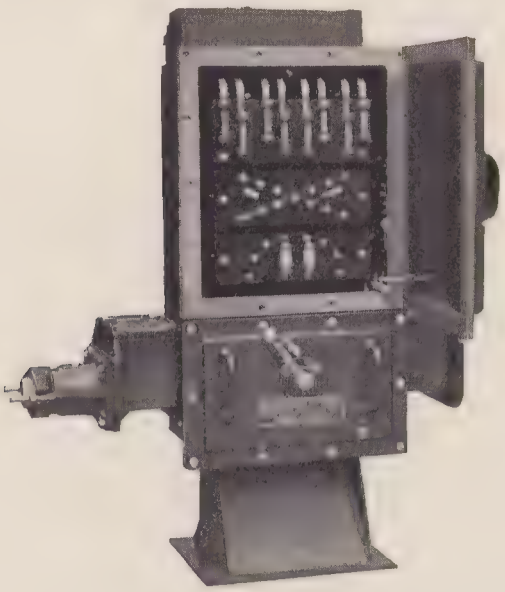


FIG. 27-13.—*Lighting Transformer Unit up to 3 kVA (The Belmos Company, Ltd.).*

are in series, the true mid-point is earthed and that the centre taps of the section windings are isolated and insulated. To enable the user to select suitable primary tappings, a voltage selection chart is provided, this chart being shown in Fig. 27-15.

For situations where only a few lights may be required, often only temporarily, the smaller unit shown in Fig. 27-16 has been developed and which provides a single-phase transformer of 0·5 kVA, wound to suit primary voltages between 400 and 625 volts and with plus and minus 5% tappings.

The transformer is protected by H.R.C. fuses and can be isolated by a push/pull double-break switch which is interlocked with the hinged cover of the transformer chamber. The illustration in Fig. 27-16 is of a unit for individual mounting. It can however be mounted as a busbar extension to other units as described in the present chapter.

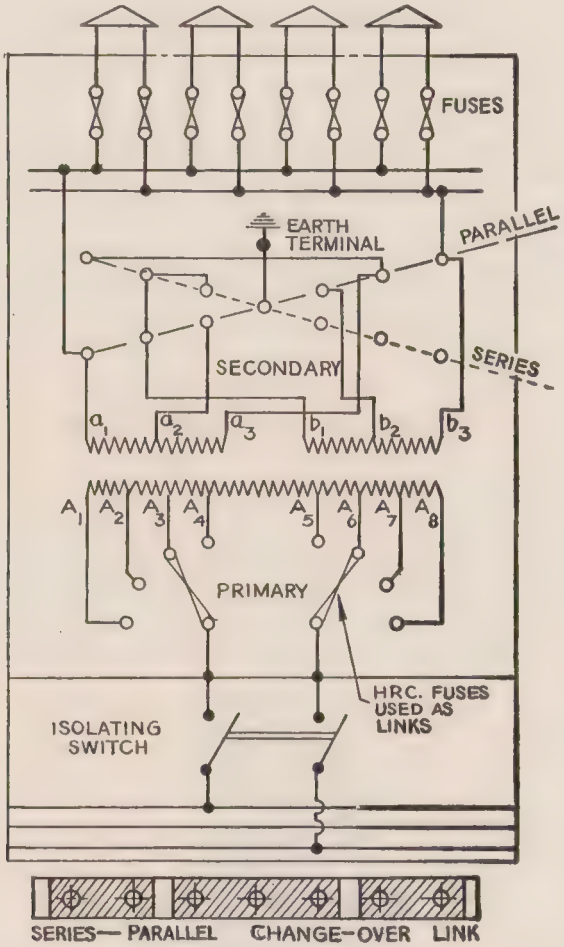


FIG. 27-14.—*Diagram of Connections of Lighting Transformer Unit (The Belmos Company, Ltd.).*

Similar in appearance and construction is a bell signalling transformer unit, in which, instead of the lighting transformer, there is accommodated a 24 VA signalling transformer with a secondary voltage of 15 volts and certified intrinsically safe by the Ministry of Fuel and Power. This unit, shown mounted as an extension to the Haulage Control Unit, Fig. 27-11, provides a ready means of signalling along the haulage.

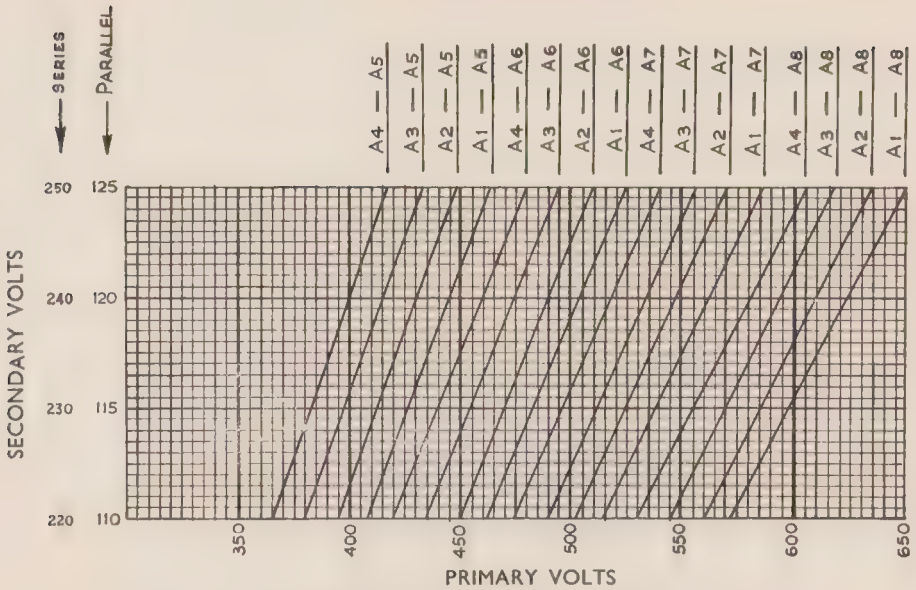


FIG. 27-15.—*Voltage Selection Chart for Lighting Transformer (The Belmos Company, Ltd.).*

Examples of use of chart.
(1) Assume primary voltage is 500 and required secondary voltage is 120 (or 240). Read vertically at 500 from base line to horizontal line marked 120/240. Tapping to choose is determined by sloping line nearest *above*; in this example the line marked A2—A6 giving a secondary voltage of 122 volts, a slight increment which will cover for drop on the secondary side. (2) Assume nominal primary voltage is 450 but is actually 440. Read vertically at latter value to 120 volt secondary line, nearest tapping line above is A2—A5 giving 122 volts. Adopt same procedure for other secondary voltages.

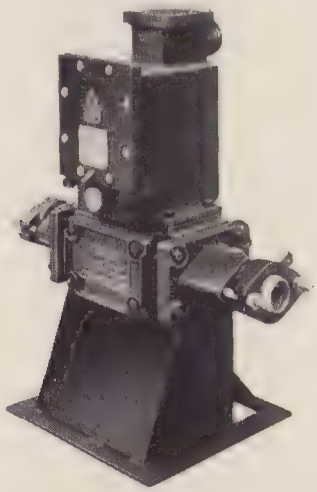


FIG. 27-16.—*Small Lighting Transformer Unit (The Belmos Company, Ltd.).*

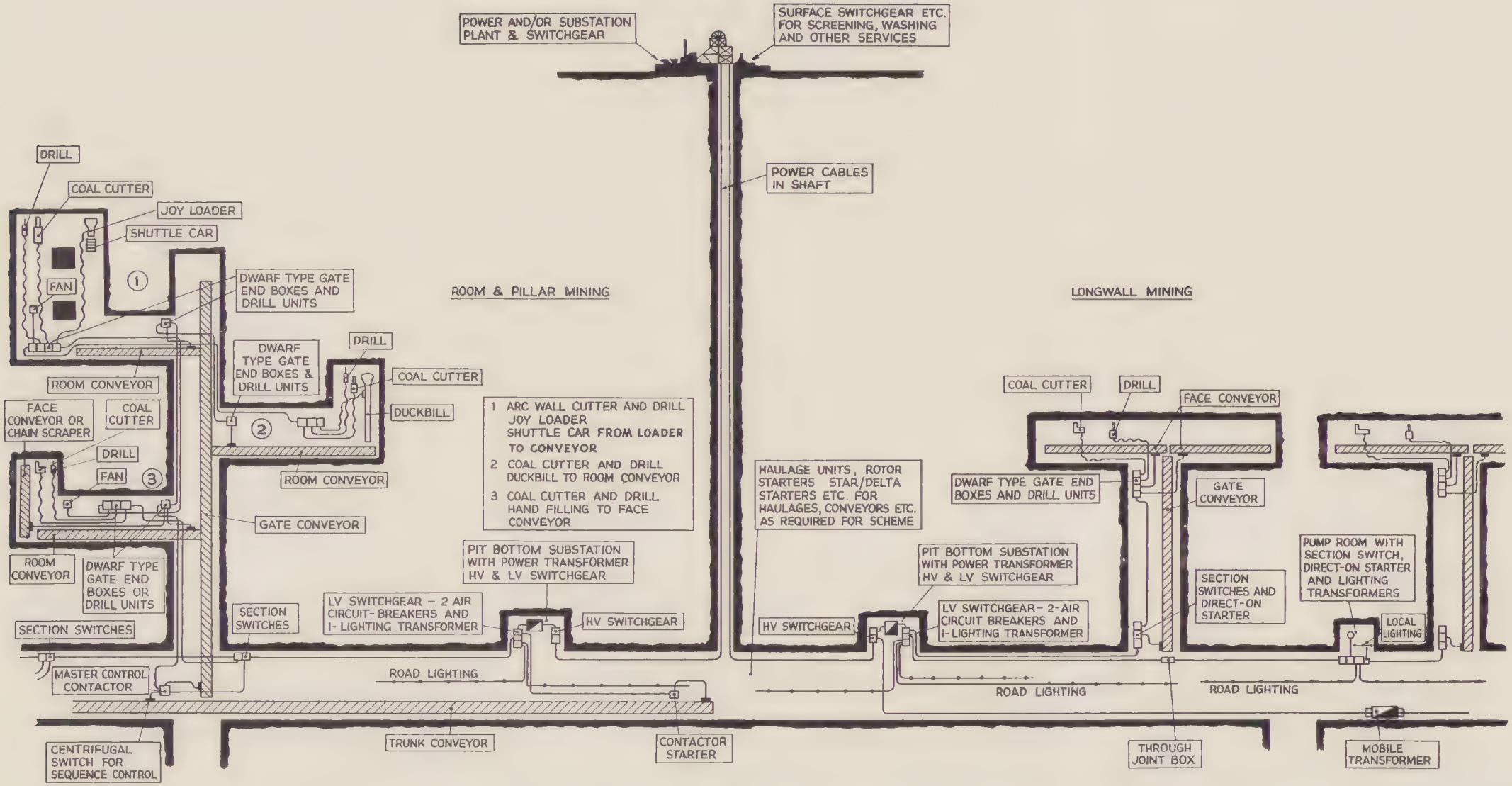

POWER AND/OR SUBSTATION PLANT & SWITCHGEAR
SURFACE SWITCHGEAR ETC. FOR SCREENING, WASHING AND OTHER SERVICES
POWER CABLES IN SHAFT
ROOM & PILLAR MINING
LONGWALL MINING
DRILL
COAL CUTTER
JOY LOADER
SHUTTLE CAR
FAN
DWARF TYPE GATE END BOXES AND DRILL UNITS
ROOM CONVEYOR
FACE CONVEYOR OR CHAIN SCRAPER
COAL CUTTER
DRILL
FAN
GATE CONVEYOR
ROOM CONVEYOR
DWARF TYPE GATE END BOXES OR DRILL UNITS
SECTION SWITCHES
MASTER CONTROL CONTACTOR
CENTRIFUGAL SWITCH FOR SEQUENCE CONTROL
DWARF TYPE GATE END BOXES & DRILL UNITS
DRILL
COAL CUTTER
DUCKBILL
ROOM CONVEYOR
1 ARC WALL CUTTER AND DRILL JOY LOADER SHUTTLE CAR FROM LOADER TO CONVEYOR
2 COAL CUTTER AND DRILL DUCKBILL TO ROOM CONVEYOR
3 COAL CUTTER AND DRILL HAND FILLING TO FACE CONVEYOR
PIT BOTTOM SUBSTATION WITH POWER TRANSFORMER HV & LV SWITCHGEAR
SECTION SWITCHES
LV SWITCHGEAR – 2 AIR CIRCUIT-BREAKERS AND 1-LIGHTING TRANSFORMER
HV SWITCHGEAR
ROAD LIGHTING
TRUNK CONVEYOR
CONTACTOR STARTER
HAULAGE UNITS, ROTOR STARTERS STAR/DELTA STARTERS ETC. FOR HAULAGES, CONVEYORS ETC. AS REQUIRED FOR SCHEME
PIT BOTTOM SUBSTATION WITH POWER TRANSFORMER HV & LV SWITCHGEAR
HV SWITCHGEAR
LV SWITCHGEAR – 2-AIR CIRCUIT BREAKERS AND 1-LIGHTING TRANSFORMER
ROAD LIGHTING
THROUGH JOINT BOX
COAL CUTTER
DRILL
FACE CONVEYOR
DWARF TYPE GATE END BOXES AND DRILL UNITS
GATE CONVEYOR
SECTION SWITCHES AND DIRECT-ON STARTER
PUMP ROOM WITH SECTION SWITCH, DIRECT-ON STARTER AND LIGHTING TRANSFORMERS
LOCAL LIGHTING
ROAD LIGHTING
MOBILE TRANSFORMER

FIG. 27-17.—*Diagrammatic Layout of Mining Practice to illustrate usage of Switchgear described in Chapter XXVII. (Not complete down to detail.)*

BIBLIOGRAPHY.

" Flameproof Switchgear " C. J. O. Garrard, M.Sc. "British Engineering" April, 1949, page 1628.

" *BS.229* " "*Flameproof Enclosure of Electrical Apparatus.*"*

A Review of Flameproof Testing 1922-1947, H. Rainford, M.B.E. H.M.S.O. 1948.*

Intrinsic Safety of Electrical Apparatus. Safety in Mines Research Paper No. 106. H.M.S.O.

Testing Memorandum No. 4, 1946. Test and certification of the flameproof enclosure of electrical apparatus. Ministry of Fuel and Power.*

" The Buxton Testing Station." H. Rainford. The Mining Electrical Engineer, 1938.

" Flameproof Enclosure of Electrical Apparatus." A survey of progress in the establishment of scientific data for design and test. H. Rainford. " The Mining Electrical & Mechanical Engineer." Vol. XXV, 1945.

" Electricity in Mines during the Year 1948." G. M. Harvey. " The Mining Electrical & Mechanical Engineer." Sept., 1949.*

Note: The student is recommended particularly to study items marked *.

CHAPTER XXVIII

REGULATIONS

In general, switchgear installations in Great Britain must comply with the Factories and Workshops Acts, the requirements of which are detailed in a Memorandum by the Senior Electrical Inspector of Factories on the Electricity Regulations. These apply to all power and substations, and the user of electrical switchgear in any form is well repaid by a study of the Memorandum numbered " Form 928 " and issued by H.M. Stationery Office (price ninepence net)*.

In addition, reference should be made to the Electricity Supply Regulations, 1937, issued by the Electricity Commissioners.

Separate regulations are issued to cover use in Mines and Quarries and reference is directed to H.M. Stationery Office publication, " Mines and Quarries Form No. 11."

Local regulations may need to be taken into account on any particular installation, and in this case onus should be on the prospective purchaser to indicate these at the time of enquiry.

It may be useful here to give a brief extract from the Electricity Regulations insofar as they affect switchgear in particular :

An " Electrical station " is defined in the Factories Act, 1937, as " any premises in which persons are regularly employed in, or in connection with the processes or operations of generating, transforming or converting, or in switching, controlling or otherwise regulating, electrical energy for supply by way of trade or for supply for the purposes of any transport undertaking or other industrial or commercial undertaking or of any public building or public institution, or for supply to streets or other public places, as if the premises were a factory and the employer of any person employed in the premises in or in connection with any such process or operation were the occupier of a factory."

The foregoing is extracted from Section 103 of the 1937 Act.

Under the heading of " Definitions," a substation is noted as :—

" Substation means any premises, or that part of any premises, in which electrical energy is transformed or converted to or from pressure above medium pressure, except for the purpose of working instruments, relays, or similar auxiliary apparatus ; if such premises or part of premises are large enough for a person to enter after the apparatus is in position."†

The foregoing, it will be seen, excludes certain kiosks, street pillars and the like in that no person can enter with the apparatus in position.

Notwithstanding, such forms of substation may still be subject to certain regulations either under the definition of " Electrical Station " or because they are on premises to which the Acts apply. It is therefore excellent practice to regard a kiosk as being subject to the regulations, and to provide the safeguards applicable.

* *Publication temporarily suspended.*

† *This definition is that given in the Electricity Regulations as distinct from the definition given in the Factories Act, 1937.*

As to " pressure," the following definitions apply :—

" ' Low Pressure ' means a pressure in a system normally not exceeding 250 volts where the electrical energy is used.

" ' Medium Pressure ' means a pressure in a system normally above 250 volts, but not exceeding 650 volts, where the electrical energy is used.

" ' High Pressure ' means a pressure in a system normally above 650 volts but not exceeding 3,000 volts, where the electrical energy is used or supplied.

" ' Extra-high Pressure ' means a pressure in a system normally exceeding 3,000 volts where the electrical energy is used or supplied."

In the case of alternating current systems the term " pressure " refers to the R.M.S. value.

Certain exemptions are laid down in regard to a number of the regulations, the full intent of which should be studied in the Memorandum referred to. These exemptions mainly concern low-pressure systems, apparatus on the supply side of consumers' terminals, situations where special conditions adequately prevent danger, and processes or apparatus used exclusively for electro-chemical or electro-termal or testing or research purposes.*

In considering the regulations, it is important to bear in mind that :—

" It shall be the duty of the occupier to comply with these Regulations. And it shall be the duty of all agents, workmen and persons employed to conduct their work in accordance with these Regulations."

This observation is worthy of particular stress in conjunction with the need for regular switchgear maintenance, dealt with fully in another chapter.

It is of importance in that gear originally supplied by a manufacturer to meet all the requirements of safety demanded, may be rendered less safe, or even unsafe, by lack of maintenance or care.

Dealing now with the Regulations as particularly applying to switchgear, it will be convenient to set down these, followed by comments which may be of help.

Regulation 1.

" All apparatus and conductors shall be sufficient in size and power for the work they are called upon to do, and so constructed, installed, protected, worked and maintained as to prevent danger so far as is reasonably practicable."

Applicable to all system pressures, it is noted that here again the word " maintained " arises. The regulation covers the need for precautions when working on live conductors such as on switchboards.

Regulation 3.

" Every switch, switch fuse, circuit-breaker and isolating link shall be (*a*) so constructed, placed or protected as to prevent danger ; (*b*) so constructed and adjusted as accurately to make and maintain good contact ; (*c*) provided with an efficient handle or other means of working,

* *Exemption 4 has a proviso which specifically qualifies the conditions under which exemption is granted and these must be noted and complied with.*

insulated from the system, and so arranged that the hand cannot inadvertently touch live metal; (*d*) so constructed or arranged that it cannot accidentally fall or move into contact when left out of contact."

In the types of switchgear outlined in the present work, the construction is generally such that danger in the manner indicated is avoided. The reference to the need for the maintenance of contacts to give good contact is important in the case of circuit-breakers where fault clearance may result in burning such that good contact is impossible.

The operation of isolating links, if of the single pole, pole operated types, demand a pole of adequate insulating properties and length. When closed, such links should be held closed by safety catch or other means. In the case of ganged isolators, a toggle or other means should hold the isolator in or out, and a definite " on " and " off " indicator should be provided.

Modern circuit-breakers are normally fitted with indicating devices to show open or closed positions.

REGULATION 4.

" Every switch intended for breaking a circuit and every circuit-breaker shall be so constructed that it cannot with proper care be left in partial contact. This applies to each pole of double-pole or multipole switches or circuit-breakers. Every switch intended to be used for breaking a circuit and every circuit-breaker shall be so constructed that an arc cannot be accidentally maintained."

The intent of this regulation is such that isolating links must not be used for breaking current. Reference has been made elsewhere to the possibility of drawing a dangerous arc under such conditions. In the case of circuit-breakers, quick-break action is provided independent of the operating handle, thus complying with the regulation.

REGULATION 5.

" Every fuse, and every circuit-breaker used instead thereof, shall be so constructed and arranged as effectively to interrupt the current before it so exceeds the working rate as to involve danger. It shall be of such construction or be so guarded or placed as to prevent danger from overheating, or from arcing or the scattering of hot metal or other substance when it comes into operation. Every fuse shall be either of such construction or so protected by a switch that the fusible metal may be readily renewed without danger."

This regulation is important in many respects. First and foremost it demands apparatus capable of adequately dealing with fault conditions. The urgency of this problem has been indicated elsewhere in Chapter XIII, and methods have been given whereby the fault conditions to be expected can be calculated with reasonable accuracy for the purpose of correct selection.

In the matter of scattering of hot metal or arcing, it demands that an air circuit-breaker shall be placed sufficiently high as to be away from an operator's face. Danger from " other substance " can mean the throwing of hot oil, and gases from the vent pipes of oil circuit-breakers and these pipes should therefore be brought out to a point remote from that where an operator should or would normally be.

An important point brought out by the regulation is that of ensuring that instrument fuses and the like should be of high rupturing capacity if they are in any part of the circuit where the full value of short-circuit may need to be interrupted by them.

As to main circuit fuses, the many excellent makes now available which comply in all respects with the regulations make the matter one of choice. Care, however, is needed in the selection of cartridge rating to ensure that the protection intended is really obtained.

REGULATION 7.

"Efficient means, suitably located, shall be provided for cutting off all pressure from every part of a system as may be necessary to prevent danger."

The need for maintenance on circuit-breakers has been stressed elsewhere. In the event of it being impossible to shut down completely as for example at week-ends or night, then isolating links to *completely* isolate the breaker are essential, and such links must be so located, with dividing barriers or screens, as to prevent danger to persons working, noting that the busbar side of such isolator can be live.

REGULATION 14.

"The general arrangement of switchboards shall, so far as reasonably practicable, be such that :—

(*a*) All parts which may have to be adjusted, or handled, are readily accessible.

(*b*) The course of every conductor may where necessary be readily traced.

(*c*) Conductors not arranged for connection to the same system are kept well apart, and can, where necessary, be readily distinguished.

(*d*) All bare conductors are so placed or protected as to prevent danger from accidental short-circuit."

Where there is any quantity of small wiring, and particularly in the case of electrically remote controlled boards, the ends of each wire can with advantage be numbered to match a detail diagram.

This is important in that in many cases wires of similar colour run in the same direction and from and to points closely adjacent.

In any case, whether the quantity of wiring is great or small, it should be run neatly and not strung from point to point. It should follow as closely as possible the runs shown on the diagram of connections.

Although not specifically mentioned in the regulation, the adequate labelling of instrument and other auxiliary fuses is equally important in tracing out circuits in the manner intended.

Accidental short-circuit, referred to in (*d*), may arise from a number of causes. Fuses or switches, where there is a risk of arcing, may, if placed close to adjacent metal, either in the circuit or not, be one cause. Conductors of opposite polarity or phase must be spaced adequately or where this is impossible, insulation introduced between.

REGULATION 15.

"Every switchboard having bare conductors normally so exposed that they may be touched, shall, if not located in an area or areas set apart for the purposes thereof, where necessary be suitably fenced or enclosed.

"No person except an authorised person, or a person acting under his immediate supervision, shall for the purpose of carrying out his duties have access to any part of an area so set apart."

As the Inspector points out in Memorandum 928, "a place set apart" means that the place shall not be used for *any* other purpose whatsoever. The regulation is one which the user must study in all its implications in relation to the situation under consideration. If the switchgear manufacturer is to provide any special precautions, these should be stated at the time of enquiry and full particulars of the conditions given.

REGULATION 16.

"All apparatus appertaining to a switchboard and requiring handling, shall so far as practicable be so placed or arranged as to be operated from the working platform of the switchboard, and all measuring instruments and indicators connected therewith shall, so far as practicable, be so placed as to be observed from the working platform. If such apparatus be worked or observed from any other place, adequate precautions shall be taken to prevent danger."

This clearly precludes the placing of such apparatus as may need to be handled or observed in normal operation at the back of a board.

In particular, instrument and other auxiliary fuses should be renewable at the front, away from any possible danger.

REGULATION 17.

"At the working platform of every switchboard and in every switchboard passage-way, if there be bare conductors exposed or arranged to be exposed when live so that they may be touched, there shall be a *clear* and *unobstructed* passage of ample width and height, with a *firm* and *even* floor. Adequate means of access free from danger, shall be provided for every switchboard passage-way.

"The following provision shall apply to all such switchboard working platforms and passage-ways constructed after January 1st, 1909, unless the bare conductors, whether overhead, or at the sides of the passage-ways, are otherwise adequately protected against danger by divisions or screens or other suitable means:—

(*a*) Those constructed for low-pressure or medium-pressure switchboards shall have a clear height of not less than seven feet, and a clear width measured from bare conductor of not less than three feet.

(*b*) Those constructed for high-pressure and extra high-pressure switchboards, other than operating desks or panels working solely at low-pressure shall have a clear height of not less than eight feet, and a clear width measured from bare conductor of not less than three feet.

(*c*) Bare conductors shall not be exposed on both sides of the switchboard passage-way unless either (1) the clear width of the

passage-way is, in the case of low-pressure and medium-pressure, not less than four feet six inches, and in the case of high-pressure and extra high-pressure not less than eight feet, in each case measured between bare conductors, or (2) the conductors on one side are so guarded that they cannot be accidentally touched."

The underlined words are important (the underlining is the author's) because of the tendency in some cases to carefully observe the prescribed clearances and then to obstruct the passage-way with loose-lying cable, or even to build, for some reason, a step. Nothing over which a man can stumble should be placed in the passage-way.

" Adequate means of access " is important. A passage-way with access (and escape) at one end only constitutes a danger in that a man working at the remote end may be trapped by fire or other cause. On the other hand, if the passage-way is very wide a second means of escape may be unnecessary where only limited power is available at the switchboard. If necessary, an escape door should be provided, particularly if the length of the board is particularly great.

In the case of equipments having doors which may be opened to 90°, the leaving of a passage-way of the minimum dimension from bare conductors, may seriously restrict the escape of a person.

It is the view of the Factory Department that the clear width of the passage-way behind any switchboard should be that indicated in the appropriate section (*a*), (*b*) or (*c*) measured from the edge of a door opened at 90°, to the wall.

Where circumstances permit, doors which open through 180° are to be preferred, while some saving in space, yet maintaining the requisite passage-way, may be obtained by double doors hinged at opposite sides, instead of one wide door.

Regulation 18.

" In every switchboard for high-pressure or extra high-pressure :—

(*a*) Every high-pressure or extra high-pressure conductor within reach from the working platform or in any switchboard passage-way shall be so placed or protected as adequately to prevent danger.

(*b*) The metal cases of all instruments working at high-pressure or extra high-pressure shall be earthed or completely enclosed with insulating covers.

(*c*) All metal handles of high-pressure and extra high-pressure switches, and where necessary to prevent danger, all metal gear for working the switches shall be earthed.

(*d*) When work has to be done on any switchboard, then, unless the switchboard be otherwise so arranged as to secure that the work may be carried out without danger, either (1) the switchboard shall be made dead, or (2) if the said switchboard be so arranged that the conductors thereof can be made dead in sections, and so separated by permanent or removable divisions or screens from all adjoining sections of which the conductors are live, that work on any section may be carried

out without danger, that section on which work has to be done shall be made dead."

Modern switchboards at high or extra high-pressure rarely, if ever, have conductors at the front and in any accessible position at the operating platform. Open types of switchgear such that are contemplated by (*a*) are very much more common on the Continent and recourse is made to guard rails, etc.

As to (*d*) emphasis has already been laid on the need for dividing screens and a recommendation made for the fitting of these initially rather than later. Fixed dividing screens are preferable to removable and temporary screens. In designing such screens care is necessary to ensure that circuit-breakers can readily be worked on. It is, however, not so easy to screen busbar isolating devices and one point on these may be alive, thus necessitating a complete shut-down, if work has to be done on such apparatus.

Sectionalising, or duplicate busbars, provide methods for overcoming shut-down but care is needed to see that in giving access to, say, one set of busbars or isolators, the other set of isolators are completely screened. Voltage transformers with self-contained high-tension fuses are often worked on without shutting down the circuit. Such work is that of renewing the fuses and means of isolation is therefore essential. Where the isolators are apart from the transformer they must be in a separate compartment. Very often in modern gear, voltage transformers are of the withdrawable type, incorporating a spring loaded or snap type switch.

If this latter type, when withdrawn, leaves live points exposed, automatic shutters become necessary to cover those points.

In connection with this Regulation, reference should also be made to B.S. 162 Part IV and its Appendices (*c*) and (*d*).

REGULATION 19.

"All parts of generators, motors, transformers, or other similar apparatus, at high-pressure or extra high-pressure, and within reach from any position in which any person employed may require to be, shall be, so far as reasonably practicable, so protected as to prevent danger."

This regulation demands little comment as it is self explanatory.

REGULATION 20.

"Where a high-pressure or extra high-pressure supply is transformed for use at a lower pressure, or energy is transformed up to above low-pressure, suitable provision shall be made to guard against danger by reason of the lower pressure system, becoming accidentally charged above its normal pressure by leakage or contact from the higher pressure system."

In the main this regulation applies solely to transformers and naturally includes instrument transformers.

REGULATION 21.

"Where necessary to prevent danger, adequate precautions shall be taken either by earthing or by other suitable means to prevent any metal other than the conductor from becoming electrically charged."

In switchgear practice, this involves earthing of metal frames, switch handles and the like, usually accomplished by the general connection of all metal work to an earth bar, which in turn is connected to the earthing system. The importance of an effective earthing system has been dealt with in a separate chapter.

REGULATION 22.

"Adequate precautions shall be taken to prevent any conductor or apparatus from being accidentally or inadvertently electrically charged when persons are working thereon."

Reference to the accident reports will confirm the importance of this Regulation.

The locking-off of circuit-breakers controlling the circuit being worked upon is perhaps the safest method with the added safeguard that the key to the lock should be in the possession of the man actually doing the work, or the supervisor or other responsible officer. The use of isolating switches on *both* sides of feeder oil circuit-breakers, or circuit-breakers on other circuits where parallel feeds may be possible, is also a recommendation.

REGULATION 23.

"Where necessary adequately to prevent danger, insulating stands, or screens, shall be provided and kept permanently in position, and shall be maintained in sound condition."

This Regulation is to advise the use of insulating stands, or rubber mats in places where persons have to handle switchgear and where there is a danger of touching bare conductors and so receive a shock to earth. The use of stands of insufficient width is to be guarded against as a man may have only one foot on the stand and the other on non-insulating flooring, such as iron plates. A width of three feet is recommended as minimum.

REGULATION 24.

"Portable insulating stands, screens, boots, gloves, or other suitable means shall be provided and used when necessary adequately to prevent danger and shall be periodically examined by an authorised person."

This Regulation has clearly the same object in view as Regulation 23 but allows the use of portable stands, etc., in circumstances where their use is so seldom required as to render permanent devices unnecessary; "other suitable means" is intended to cover insulated spanners, screwdrivers, pliers, etc. The proviso demanding periodical inspection is vitally important, particularly in the case of rubber gloves and insulating boots. Suppliers of such items will generally carry out inspection at *regular* intervals at a nominal charge.

REGULATION 25.

"Adequate working space and means of access, free from danger, shall be provided for all apparatus that has to be worked or attended to by any person."

Safe and adequate space is essential where any person has to work on switchgear.

By safe, it may be meant not only electrically but also physically—as for example means may have to be provided to allow a hand-hold for a man.

REGULATION 26.

"All those parts of premises in which apparatus is placed shall be adequately lighted to prevent danger."

As example, if back access is provided to a cubicle type switchboard, then adequate lighting is necessary to prevent danger. Lights so placed to accomplish this need not be constantly burning and the switch for operating them must be away from the danger area.

REGULATION 27.

"All conductors and apparatus exposed to the weather, wet, corrosion, inflammable surroundings or explosive atmosphere, or used in any process or for any special purpose other than for lighting or power, shall be so constructed or protected, and such special precautions shall be taken as may be necessary adequately to prevent danger in view of such exposure or use."

In other words, special risks mean special precautions.

REGULATION 28.

This regulation is not quoted here in full as it bears directly on all electrical equipment and defines the law regarding *authorised* persons permitted to work where technical knowledge or experience is essential to prevent danger.

CHAPTER XXIX

MAINTENANCE, ERECTION AND TESTING

From one point of view the static nature of electrical switchgear is a disadvantage. This is because, unlike rotating machinery, it does not appear to be needful of any maintenance. Attention to this problem has been focussed recently by the issue of B.S. 1086, " A Code of Practice for the Maintenance of Switchgear " and all users of switchgear should have this available for study and reference as an authoritative document. Quite a large number of operational difficulties which arise in service can be traced to inadequate maintenance ; often to a complete lack of maintenance. A smaller number of major difficulties can be attributed to the same cause although the establishment of this is difficult because the cause is so often destroyed by the event, *e.g.*, an accumulation of dust and damp leading to flashover or worse. There is, then, very good reason why electrical switchgear should receive *regular* and *detailed attention*, and the less real work the gear has to do, the more urgent is the need. The notes which follow will be of assistance in the preparation of a scheme which should be formulated to suit the installation.

Any system of maintenance demands as a first requisite an orderly programme with predetermined intervals between inspections. It demands that a full record be kept of each inspection, the work done or the adjustments made (even to such a detail as an adjustment of a trip setting), the work or adjustments necessary but which cannot be carried out there and then, and, to be orderly, special tools, spares, etc., must be at hand.

Switchrooms must not be used, as they so often are, as storerooms for articles unrelated to the switchgear, and tidiness is a major essential. Too often do operators and maintenance staff leave miscellaneous sundries disposed on or about the gear, *e.g.*, rags, spare compound.

Special instruction books issued by makers of specialised equipment, *e.g.*, protective gear, should be to hand and kept in a suitable receptacle at the site rather than in a central Office elsewhere. A useful cupboard for housing spare parts, instruction books, diagrams, etc., is shown in Fig. 29-1.

Before any work is carried out suitable measures must be taken to guard against danger. It is the responsibility of the occupier to ensure the safety of those whom he deputes to work on the switchgear and a system must be worked out beforehand which will provide adequate safeguards and will nominate the person who will be responsible for the working of the system. No attempt will be made here to outline such a scheme, because so many variations are possible to suit individual installations. Generally, any scheme should include a permit card authorising the work to be done, the card being issued only by the responsible person previously mentioned. The card should clearly indicate without any possible doubt the points at which it is safe to work, the times when it can be done, the steps taken to ensure safety, such as earthing, isolation, danger notices, locked-out points, etc., and the nearest live point. It should bear the signature of the responsible

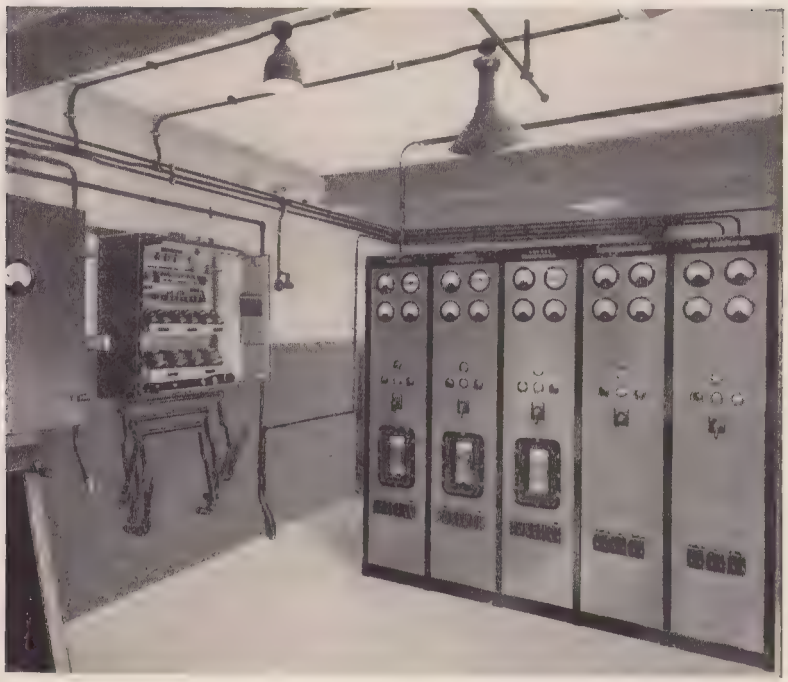


FIG. 29-1.—*Substation control room showing spares cabinet on wall. Cabinet also contains drawings and instruction books (J. & P. Ltd.).*

person and after the work is completed should be cancelled and removed from the possession of those doing the work.

Danger notices should only be put up or removed by the responsible person who will take personal charge of any keys used to lock-out items of equipment. The most careful handling of keys is important. More accidents occur due to the wrong use of these, unknown duplicates, etc., than by other causes. They lead to considerable carelessness, often by operatives whose knowledge should call for extra vigilance.

The foregoing may appear somewhat stringent for small installations, but it must not be overlooked that the electricity is just as lethal on the simple installation as on the very largest and that 400 volts has caused as many deaths as voltages of a higher order. It must also be borne in mind that on the small installation the available staff is not so highly trained. Reference to the catalogue of electrical accidents issued yearly by the Ministry of Labour and National Service will confirm this and be a reminder of the great need for care.

The planning of a system of maintenance can be considerably eased if, in the first place, thought is given to the risks and hazards which can arise. For example, dust and damp are two evils so often found in switchrooms as

to indicate that little appreciation exists of the hazards they produce. A thought given to this when constructing the switchroom can relieve the work of the maintenance staff. Moisture is always a potential danger and is not cured by having a hot room. Normal temperature variations in a room result in condensation and this, particularly if coupled with dust and dirt will sooner or later lead to trouble. The solution is adequate ventilation and a room kept at an *even* temperature. Dust is often present due to the sweeping of ordinary concrete floors. This can be mitigated by the use of one of the paints available which make such surfaces non-dusting, adding, incidentally, to the appearance of the room.

Other precautions in the original planning which are worthy of thought are :—

(1) Fireproof doors, roofs and ceilings.
(2) Sealing of cable ducts.
(3) Installation of fire fighting apparatus.
(4) Subdivision of switchgear.

Of the many items which need inspection and maintenance, the circuit-breaker is perhaps most important. On this depends the establishment and interruption of current under both normal and abnormal conditions. It will be considered first, followed by other details.

Circuit-Breakers.

Under normal operating conditions a periodic check should be made on the following.

(*a*) Check level and condition of the oil. Clean insulators and occasionally examine the contacts to assure that good contact is being maintained. Arcing contacts should be watched for burning ; operating mechanisms should be checked and lubricated.

(*b*) Check the tripping of the breaker through the devices which will have to function on fault or overload, *e.g.*, direct acting trip coils or relays. In the case of relays, operate these manually, *e.g.*, by turning the disc.

(*c*) Check indicating devices, such as mechanical on and off indicators, as an incorrect indication may at some time lead to a fatal accident.

(*d*) Check auxiliary switches for cleanliness and contact making.

(*e*) Check all units and joints, particularly in heavy current installations.

After a circuit-breaker has operated under fault conditions, it should be examined as soon as possible thereafter.

This is important, as while it is accepted that after such an operation the circuit-breaker should be capable of being closed and of making, breaking and carrying its *normal* current, its breaking capacity for a subsequent fault may be impaired.

It is obvious that the restoration of the original condition is paramount and the following attention is essential.

(*a*) Examine the oil and if badly discoloured change or recondition. If in good condition, check level to see that this has not fallen by an amount likely to impair future operation. Oil in good condition should withstand 30 kV for one minute, in a standard oil testing cup with 0·15 inch gap between electrodes.

(*b*) Tank should be lowered and all contacts examined. Arcing contacts must be replaced, or beads of fused metal removed and pitted surfaces cleaned up with a smooth file. Care should be taken to prevent filings falling into the tank.

(*c*) Inspect insulation for possible damage. Carefully clean the surfaces to remove deposits of carbon. Similarly, arc control devices must be cleaned of carbon. In some designs, replacement of arc-splitting plates is necessary if these have become charred. When cleaning insulators, use a fabric which will not deposit loose fibres. Bakelised paper insulator surfaces may be scratched, and after removing any roughness with fine sandpaper, they should be given two coats of special varnish.

(*d*) Check closing and tripping mechanisms.

(*e*) Make a final inspection to ensure that no tools have been left in the tank, that the tank linings and barriers are in position and secure, and that the tank gasket is in good condition.

CONTACTS.

In any switchgear installation there are a variety of contacts other than those in the circuit-breaker. Upon the efficiency of these much depends.

A first essential is that all contact surfaces shall be kept clean and that effective pressure be maintained. Any dirt or oxide on the surfaces causes high resistance and is the beginning of overheating. A common cause of contact trouble is the softening of backing springs due to temperature.

The formation of oxide on contacts must be particularly looked for as this can become really serious and a vicious circle is possible -oxide-high temperature—more oxide—higher temperature.

Sliding contact surfaces should be kept smooth. The effectiveness of the contact however is dependent on pressure.

The old method of checking with a ·002 in. feeler is no guide as it is unlikely when two plane surfaces are brought together that they will be in contact all over and while a feeler test may prove that the edges are in contact there may be a measurable gap at points where the feeler cannot be applied.

Contacts on auxiliary switches, control switches, etc., are usually of a simple type but on them depends the correct functioning of many other items of equipment, not the least of which is protective gear. These contacts must be clean, as a small particle of grit may be sufficient to keep them apart.

The bolted type of contact, as where connections join busbars, or breaker stems, or where wiring connects to instruments or relays, depend on the tightness of the nuts. The habit which nuts have of coming loose is well known, and happens in spite of all precautions. It is important to check for tightness at regular intervals. If for any reason a bolted joint is broken down, the surface should be cleaned before remaking.

Where two surfaces are bolted together, vaseline and scratch brush should be applied just prior to remaking.

OPERATING MECHANISMS.

The intelligent application of a small quantity of lubricant is an essential

to satisfactory operation. A "small quantity" is emphasised because excess oil or grease finds its way to other parts, *e.g.*, trip coil plungers, and effectively stop those parts from operating as intended. It is recommended that maintenance on operating mechanisms should include inspection for this possibility.

The correct lubricant to apply to any mechanism or part of it must depend on the design and the guidance of the maker should be sought. In some cases, makers send out mechanisms sprayed with a rust-resisting compound which is also slightly lubricating. This compound should *not* be removed.

During maintenance, old oil or grease with the dust it has probably collected, should be cleaned away before applying new oil or grease.

Check nuts for tightness, and pins and split pins for correctness of fitting.

Control Panels and Wiring.

Few control panels are really dust tight. Clearances between contacts and terminal stems on control and instrument switches, terminal blocks and lamp terminals, are relatively small and dust can accumulate between them to an extent that even the low potential which exists between adjacent stems may cause breakdown. This type of apparatus can be kept clean by the use of bellows or better still, the vacuum cleaner.

It is vitally important to check indicating lamps as on these a correct knowledge of circuit conditions must depend. This is particularly the case where a single lamp is used and it is not known whether it may have suffered mechanical damage. Wiring on control panels should be checked with a megger at intervals of say once a year. Earth connections should also be checked for continuity.

Fuses, too, are all important. Those of the cartridge type can be checked by keeping a record of resistance. Wire fuses should be examined visually.

When rewiring, always use the correct gauge of wire.

Protective Gear.

Protective gear is installed for the purpose of disconnecting the apparatus from the electrical system when that apparatus or its connecting conductors become faulty. By this means extensive damage involving a major shut-down may be avoided. It is of primary importance therefore that protective gear be kept in sound condition *at all times*, and to this end a regular check on its functions is essential.

It is particularly important that a check be made after any maintenance operation which may have necessitated disturbing certain connections.

Many protective systems in use to-day are of a special type (see Chapter XX) and with these, the makers usually issue instruction booklets to cover both the operation, testing and maintenance. In the simpler forms of protective gear the most satisfactory test is to simulate a fault by passing current through the windings of the protective transformers causing the gear to function as intended.

Relays must be kept clean, the contacts being checked to make sure that contact does actually occur.

Settings should be checked and connections to relays be tight under the nuts on the stems. Corrosion of connections should be looked for particularly in damp situations, where corrosion occurs, mainly on d.c. connections, *e.g.*, trip circuits.

BATTERIES.

Usually employed for the closing operation of the circuit-breaker or the trip coils, indicating devices, etc., it is essential that batteries be maintained in sound condition.

This can usually be checked from the specific gravity of the electrolyte, which should be maintained at its correct level. Connections should be tight and corrosion checked by smearing the terminals with petroleum jelly.

Trip batteries are usually of the nickel iron type and require little attention. They are supplied in cabinets which accommodate test switches and instruments (see Chapter XXVI).

ERECTION ON SITE.

Owing to the many variations in design of electrical switchgear, no fixed rules can be set down to cover the essentials of satisfactory erection on site. In many cases, the makers issue individual instructions for use when their own erection staff are not called upon to undertake the work.

A chief essential of all types, however, is that of having a true and level foundation, and the careful lining up of the gear on this foundation prior to final joining up, using where necessary shims to adjust for small inaccuracies. It is vitally important that in types of gear where there is a fixed housing into which a moving carriage has to enter that the housing be plumb. In types of gear where compounding has to be done on site, e.g., in compound filled switchgear at joints between adjacent units, care should be taken to follow closely the manufacturers' instructions.

SITE TESTING.

It is often the case that switchgear is installed in a switchroom some time before it is commissioned. It may be that the room has not been dried out and that other contractors are still working in the room. Such conditions warrant a careful examination of the gear before commissioning, ensuring that every detail is dry and clean, that working parts are properly lubricated, etc.

Wedges (as in oil circuit-breakers) which may have been used to prevent damage in transit should be removed. If any special precautions must be taken, these are usually indicated by tags tied to the gear. It is recommended that these be removed by a responsible person only and *not*, as is so often the case, by a stores receiving clerk before the apparatus reaches the final site. Such instructions usually cover the need to fill voltage transformers with oil, the removal of protective shrouds from bakelised paper bushings, and the removal of paper wedges from protective relays.

Megger tests should be carried out on both primary and secondary circuits using a 1,000 volt megger. If damp is present unsatisfactory readings may be obtained. In this case, wipe all insulating surfaces with a warm dry cloth. In the extreme case it may be necessary to dry out the gear by other means. If resorted to, radiators or heaters should be placed so that there is no danger of blistering the surfaces of the insulation.

Pressure tests should subject all main connections to twice the service voltage plus 2,000 volts for one minute, at a frequency of 50 cycles per second. If tests of a longer duration are required, then the voltage should be reduced in line with the following :—

Duration of Test	Percentage of Standard Test Voltage
Minutes	
1	100
2	83·5
3	75·0
4	70·0
5	66·6
10	60·0
15	57·7

It often occurs that d.c. pressure tests have to be applied, owing to the length of connected cable. The latter would demand such a high charging current as to make the size of testing transformer for a.c. very large and unwieldy. The correct d.c. voltage to apply is $\sqrt{2}$ times the r.m.s. value of the a.c. test voltage. In all cases of d.c. testing the manufacturers agreement should be obtained, notably because the usual time of application to cables is 15 minutes.

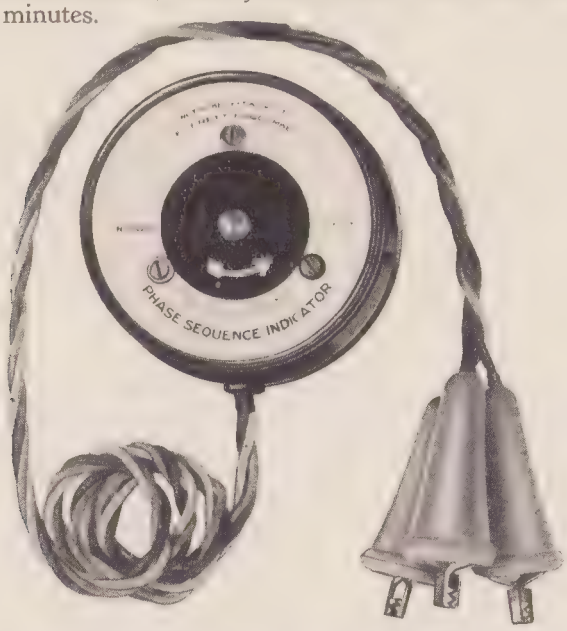


FIG. 29-2.—*Phase Sequence Indicator (Everett Edgcumbe & Co. Ltd.).*

Repeated pressure testing is generally deprecated as while a breakdown may not occur immediately, the insulation is stressed and repeated stressing may in time be the cause of breakdown. In any event, it is well to remember that the gear has always been pressure tested at the makers' works and in

many cases further high pressure tests might be dispensed with without danger. It may be wise however to pressure test the busbars on compound filled gear on site as these are never completely finished at the joints at the works.

Generators, transformers and feeders must be phased out. In the case of generators, the phase rotation of the generator must be checked against the system it is to serve. For this purpose a phase-rotation meter is useful but other methods include checking against an induction motor of known rotation or by lamps across the secondaries of suitable voltage transformers. A typical phase-rotation meter is shown in Fig. 29-2. In the case of transformers where these operate in parallel, not only must a rotation check be made, but they must be phased-out on each phase. All feeders must be similarly phased out, verifying each phase in turn and simultaneously proving continuity.

BIBLIOGRAPHY.

B.S. 1086.

The Switchgear Handbook, W. A. Coates and H. Pearce (Pitman and Sons).

Electric Power Stations, T. H. Carr (Chapman and Hall).

APPENDIX A

A NUMERICAL EXAMPLE OF THE STABILITY OF PROTECTIVE GEAR ON THROUGH FAULTS

In the "J. & P. Transformer Book," a study is made of earth faults in transformers in parallel by the method of symmetrical components. The example taken for the study is a system comprising two 5,000 kVA transformers stepping down from 33,000 volts to 11,000 volts, and two 1,500 kVA transformers again stepping down from 11,000 volts to 440 volts, to supply a consumer's load. The line diagram is that shown in Fig. A-1.

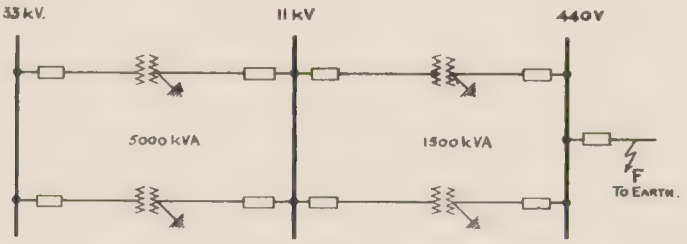


Fig. A-1.

In the course of the study it is shown that the fault current distribution on the occurrence of an earth fault at "F" is as shown in Fig. A-2 (reproduced from Fig. 527, "J. & P. Transformer Book"), and assumes that neutral point of the 440 volt Star winding is earthed solidly.

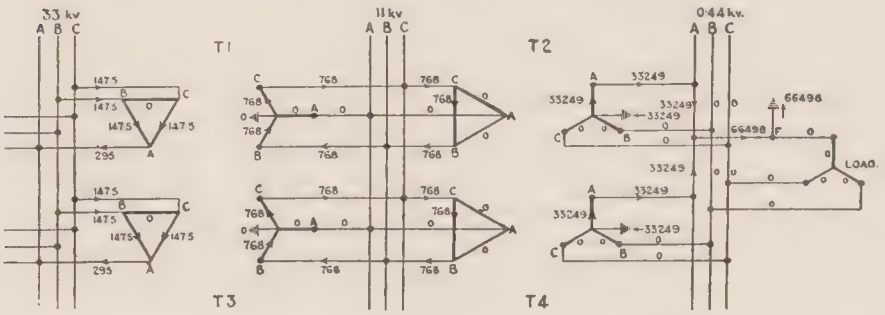


Fig. A-2.

In Chapter XX, stress has been laid on the necessity for stability of protective gear during through faults. An examination of the diagram Fig. A-1 shows that in the case chosen it is essential that only the circuit breaker controlling the faulty feed shall open, thus causing no disturbance or shut-down on any other section.

It will be noted in Fig. A-2 that there is complete inequality of primary current, and it would appear that under such circumstances any form of balanced protective gear would operate to disconnect *all* transformers, thus shutting down the system.

In order to demonstrate that this is not the case, it is assumed that the two 33/11 kV transformers are each protected by circulating current protection as described in Chapter XX, and the circuit for each of these transformers would be that shown in Fig. A-3.

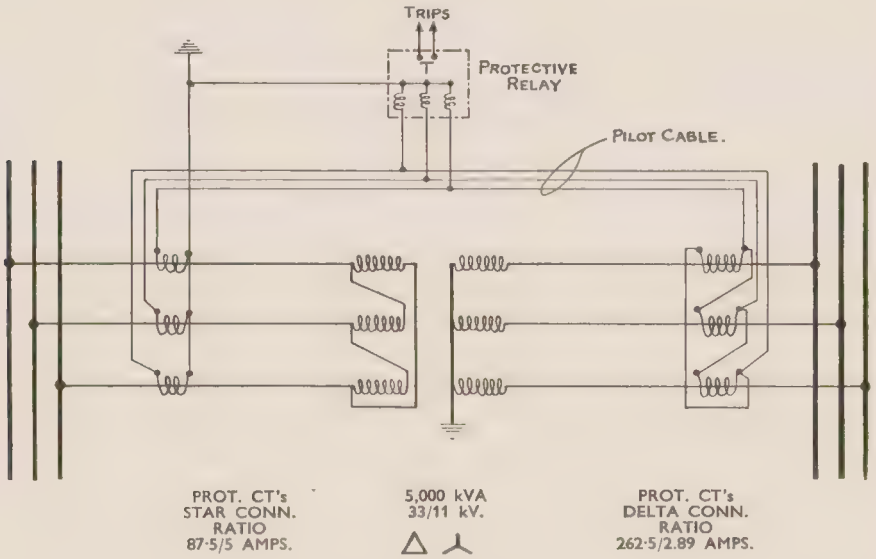


FIG. A-3.

Dealing with the current transformers shown on the 33 kV side, which have a ratio of 87·5/5 amperes, it will be seen that based on the fault currents in Fig. A-2 the secondary currents produced by the fault primary currents are :—

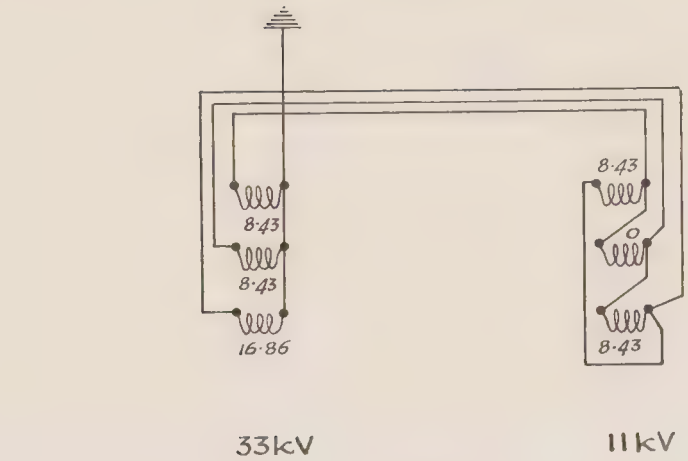
Primary 295	Secondary 16·86
Primary 147·5	Secondary 8·43
Primary 147·5	Secondary 8·43

while on the 11 kV side, where the normal ratio is 262·5/2·89 amperes, the figures are :—

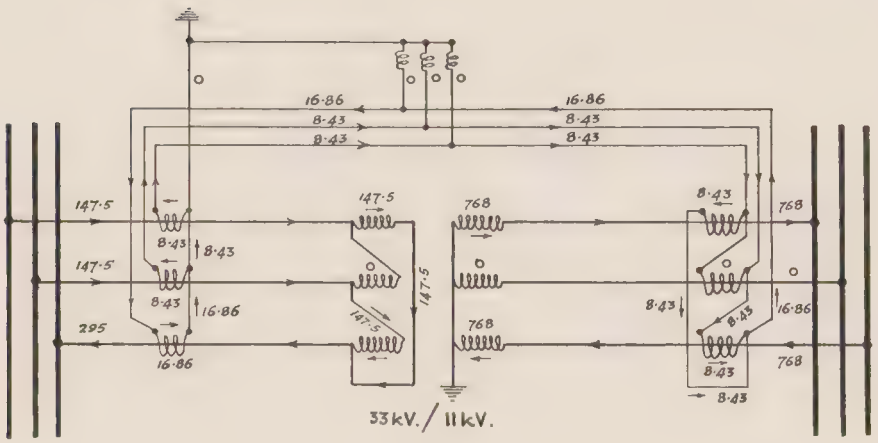
Primary 768	Secondary 8·43
Primary 0	Secondary 0
Primary 768	Secondary 8·43

It will be noted that the figures of secondary current are now resembling each other, except for that of 16·86 amperes on the 33 kV side, and that of 0 amperes on the 11 kV.

In diagram form and omitting the main connections, these figures can be shown as in Fig. A-4 (*a*).



(*a*)



(*b*)

FIG. A-4.

Imposing this diagram (Fig. A-4 (*a*)) on the main diagram, and indicating the values and direction of both primary and secondary currents, we obtain Fig. A-4 (*b*), from which it will be noted that, by the combination of the star and delta secondary currents, complete balance is obtained in the pilots and under such conditions, the protective relay does not operate, leaving the transformers in service in spite of what, at first sight, appears to be unbalance.

Similarly, taking the 11,000/440 volts delta star transformer, it can be equally well shown that the secondary currents due to the fault currents, shown in Fig. A-2, will be of the magnitudes and directions given in Fig. A-5 (omitting all main connections), and again showing a condition

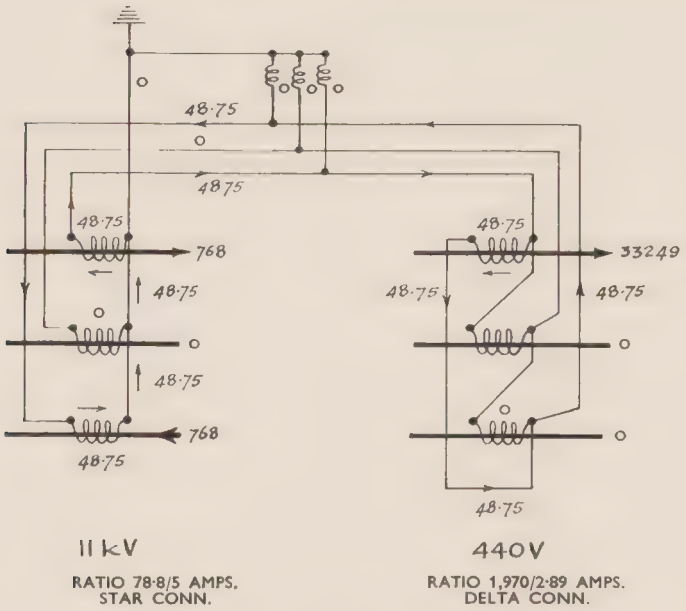


FIG. A-5.

of balance in spite of apparent unbalance due to earth fault.

If we now assume that, instead of circulating current protection, restricted earth fault protection had been applied to both sides of the transformers, it will be again seen that operation will not occur.

Figs. A-6 and A-7 set out the connections for this form of protection, together with magnitudes and direction of secondary currents (as obtained from previous examples).

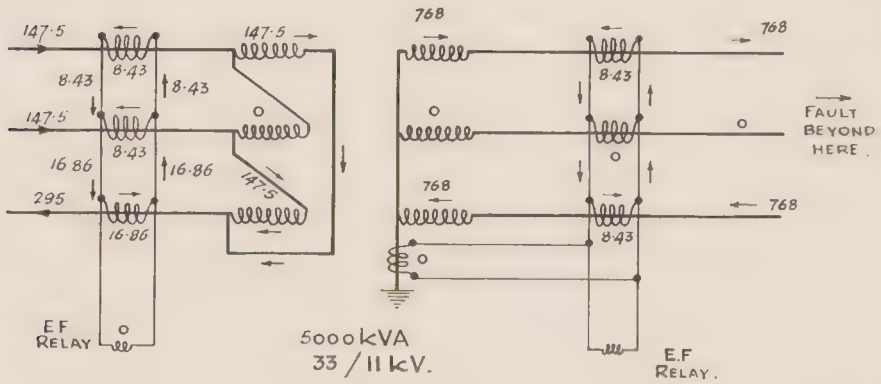


FIG. A-6.

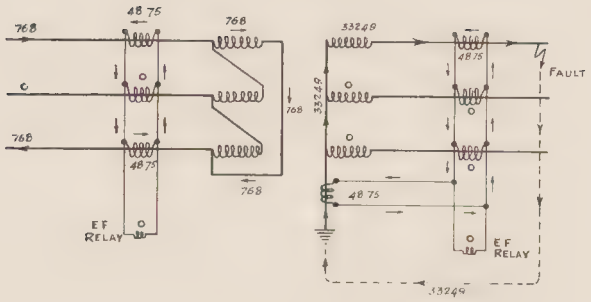


FIG. A-7.

Had the fault occurred, however, *within* the protected zone of, say, the 11,000/440 volt transformer, at a point F in Fig. A-8, it will be seen that this would cause relay operation on the l.v. side. By suitable intertripping arrangements such relay operation would bring out both h.v. and l.v. breakers.

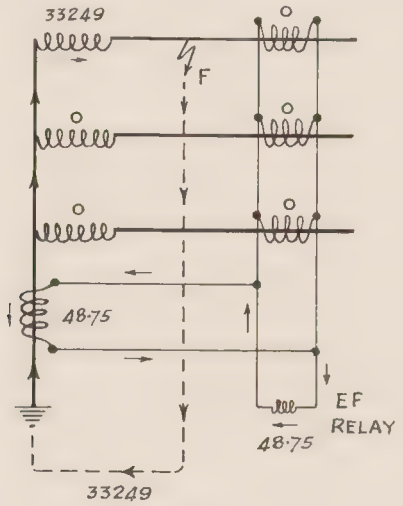


FIG. A-8.

APPENDIX B

A STUDY IN FUSE PROTECTION

It has been indicated in Chapter V how certain classes of apparatus can be economically controlled and protected by means of fused switchgear, i.e., gear having fuses to back it up in the event of short-circuit. Where such switchgear is used to control both the primary of a power transformer and the feeders on the low-voltage side of that transformer, it is essential that for faults on the feeders, the l.v. fuses should operate to clear the fault and that the h.v. fuse remains intact.

For the purpose of studying this, the system shown in Fig. B-1 has been chosen, being one which is in actual operation in a railway sub-station. It will be noted that the primary side of the 500 kVA transformer is controlled and protected by a load-breaking switch and 75 amp. fuse of the type described in Chapter V, while the l.v. feeders are fitted with air circuit-breakers and fuses of the type described in Chapters VI and XI, the l.v. fuses being variously rated at 60, 200 and 400 amps.

It is necessary in this study to consider three types of fault, viz :—

(*a*) Three-phase symmetrical.
(*b*) Line to line single phase.
(*c*) Line to earth.

For the purpose of the study, the calculations will ignore the cable connections as these are relatively short. For the earth fault condition it will be assumed that the earth resistance is of the order of 2 ohms., with a revised calculation if this could be reduced to 0.2 ohms.

The data essential for the fault current calculations are as follows :—

H.V. Network :	Fault Capacity 250 MVA.
Power Transformer :	500 kVA.
	Voltage Ratio 6,300/400.
	Delta/Star.
	Line Current h.v. 46A.
	l.v. 720A.
	Reactance . 4%.
	Resistance 1·28%.
Earth Resistance :	2 ohms.

The calculations may now proceed as follows :—

Equivalent impedance of h.v. network :—

$$ZH = \frac{kVA \times 100}{MVA\ Fault\ capacity \times 1{,}000}$$

$$= \frac{500 \times 100}{250 \times 1{,}000} = 0{\cdot}2\%$$

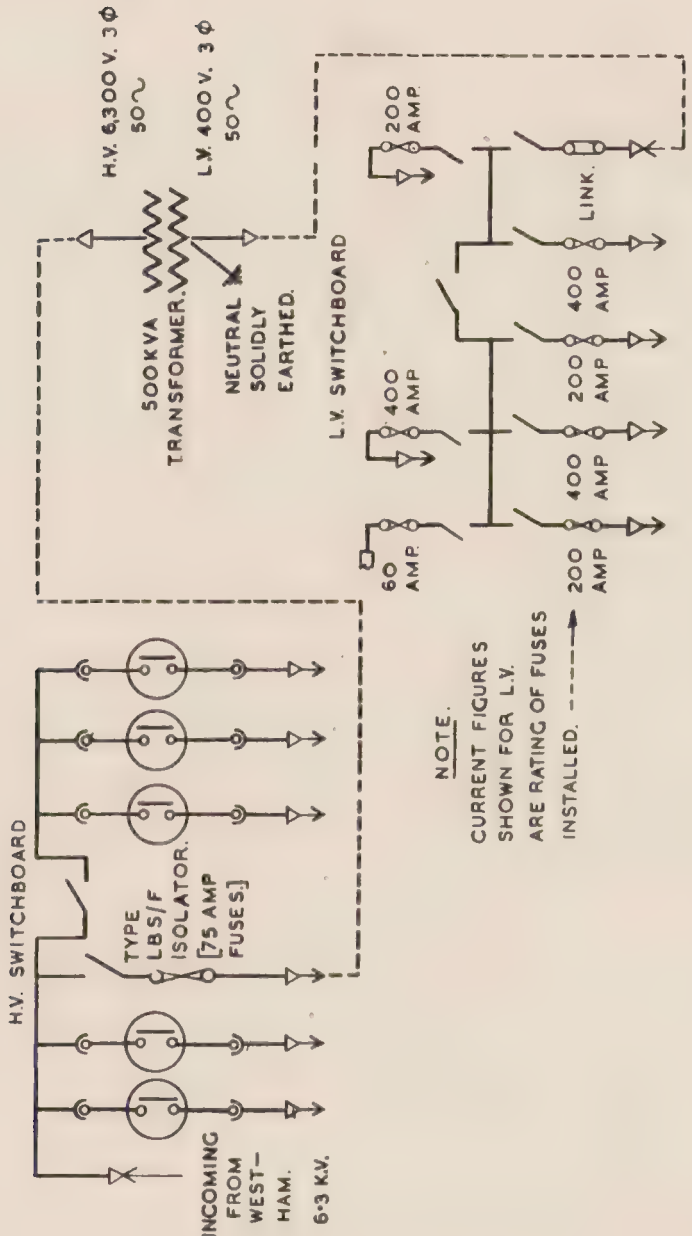

H.V. 6,300 V. 3 Φ
50 ~
L.V. 400 V. 3 Φ
50 ~
500 KVA
TRANSFORMER.
NEUTRAL
SOLIDLY
EARTHED.
L.V. SWITCHBOARD
200 AMP.
400 AMP.
LINK.
400 AMP
200 AMP
400 AMP
60 AMP.
200 AMP
H.V. SWITCHBOARD
TYPE LBS/F ISOLATOR. [75 AMP FUSES.]
INCOMING FROM WEST-HAM. 6·3 K.V.
NOTE.
CURRENT FIGURES SHOWN FOR L.V. ARE RATING OF FUSES INSTALLED.

FIG. B-1.

Impedance of Power Transformer :—

$$ZT = \sqrt{4^2 + 1{\cdot}28^2} = 4{\cdot}2\%$$

Impedance of Earth Connection :—

$$ZE = \frac{100{,}000 \times kVA \times R}{E^2}$$

$$= \frac{100{,}000 \times 500 \times 2}{400 \times 400} = 625\%$$

where E = line voltage in volts.
R = resistance in ohms.

Now Z_1 and Z_2 the positive and negative phase sequence impedances (see pages 280, 281 etc.) are, for the class of apparatus under consideration, equal. Therefore, $Z_1 = Z_2 = 4{\cdot}2\% + 0{\cdot}2\% = 4{\cdot}4\%$. The zero phase sequence impedance Z_0 is three times the single value ZE calculated above as it is in series with each branch of the network. Therefore $Z_0 = 3 \times 625 = 1{,}875\%$. The zero phase sequence impedance of the transformer will be ignored as it is equal only to Z_1 or Z_2, i.e., $4{\cdot}2\%$ and this is so small compared with the $1{,}875\%$ value as to be swamped.

If I is the normal full load current on the secondary side of the transformer, then for

(*a*) *a three-phase symmetrical fault*

$$\text{S.C. Current} = \frac{I \times 100}{Z_1}$$

$$= \frac{720 \times 100}{4{\cdot}4} = 16{,}360 \text{ A.}$$

(*b*) *a line to line fault.*

$$\text{S.C. Current} = \frac{\sqrt{3} \times I \times 100}{Z_1 + Z_2}$$

$$= \frac{\sqrt{3} \times 720 \times 100}{4{\cdot}4 + 4{\cdot}4} = 14{,}153 \text{ A.}$$

(*c*) *a line to earth fault.*

$$\text{S.C. Current} = \frac{3 \times I \times 100}{Z_1 + Z_2 + Z_0}$$

$$= \frac{3 \times 720 \times 100}{4{\cdot}4 + 4{\cdot}4 + 1875} = 115 \text{ A.}$$

These values of faults current are those which can appear at faults on any of the l.v. feeders at points close up to the fused circuit-breakers, and which the latter must clear. Such faults will, of course, give rise to values of current much higher than normal on the primary side of the transformer and these values are calculated as follows :—

(*a*) *three-phase symmetrical fault.*

Current will be present in each of the three primary lines in inverse

proportion to the line voltage ratio of the transformer, or, in direct proportion to the normal ratio of current transformation, *i.e.*, as 46 : 720.

Thus the current in each line is

$$\frac{46}{720} \times 16{,}360 = 1{,}045 \text{ A.}$$

(*b*) *line to line fault.*

As two secondary lines are faulted, two primary lines will be affected and carry fault current in inverse proportion to the ratio of tranformation, viz :

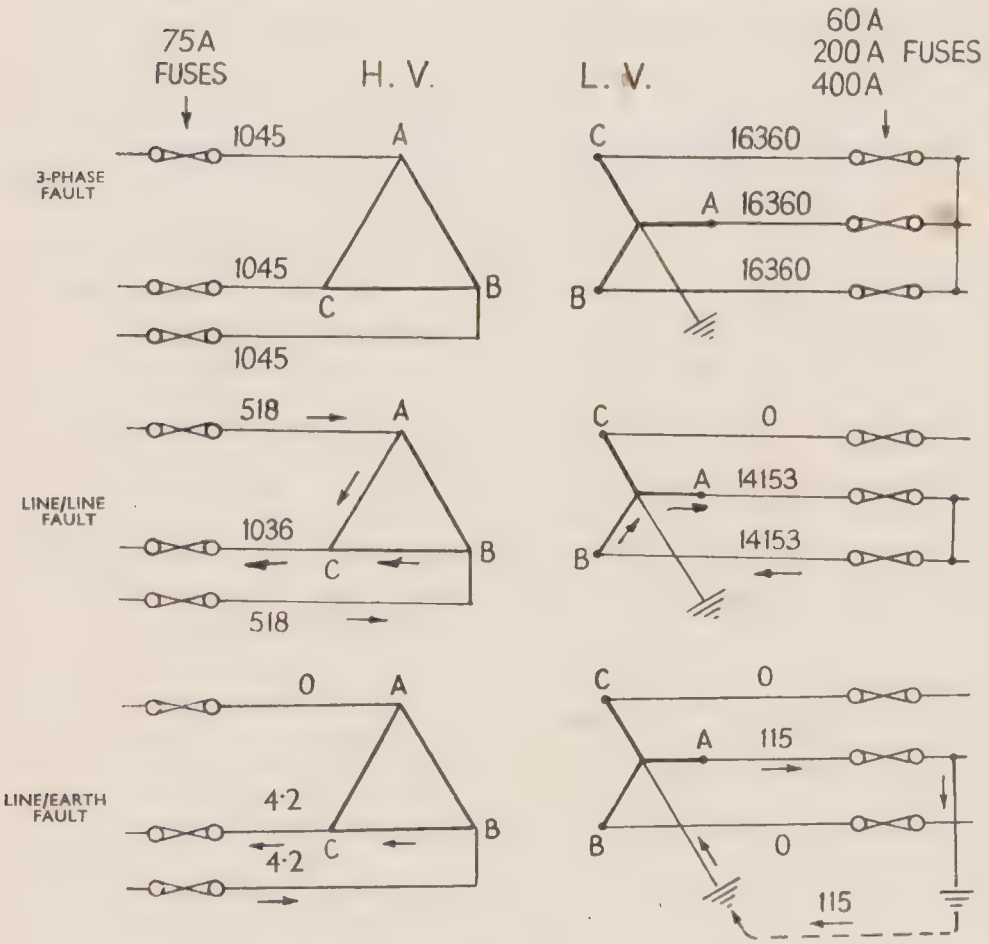
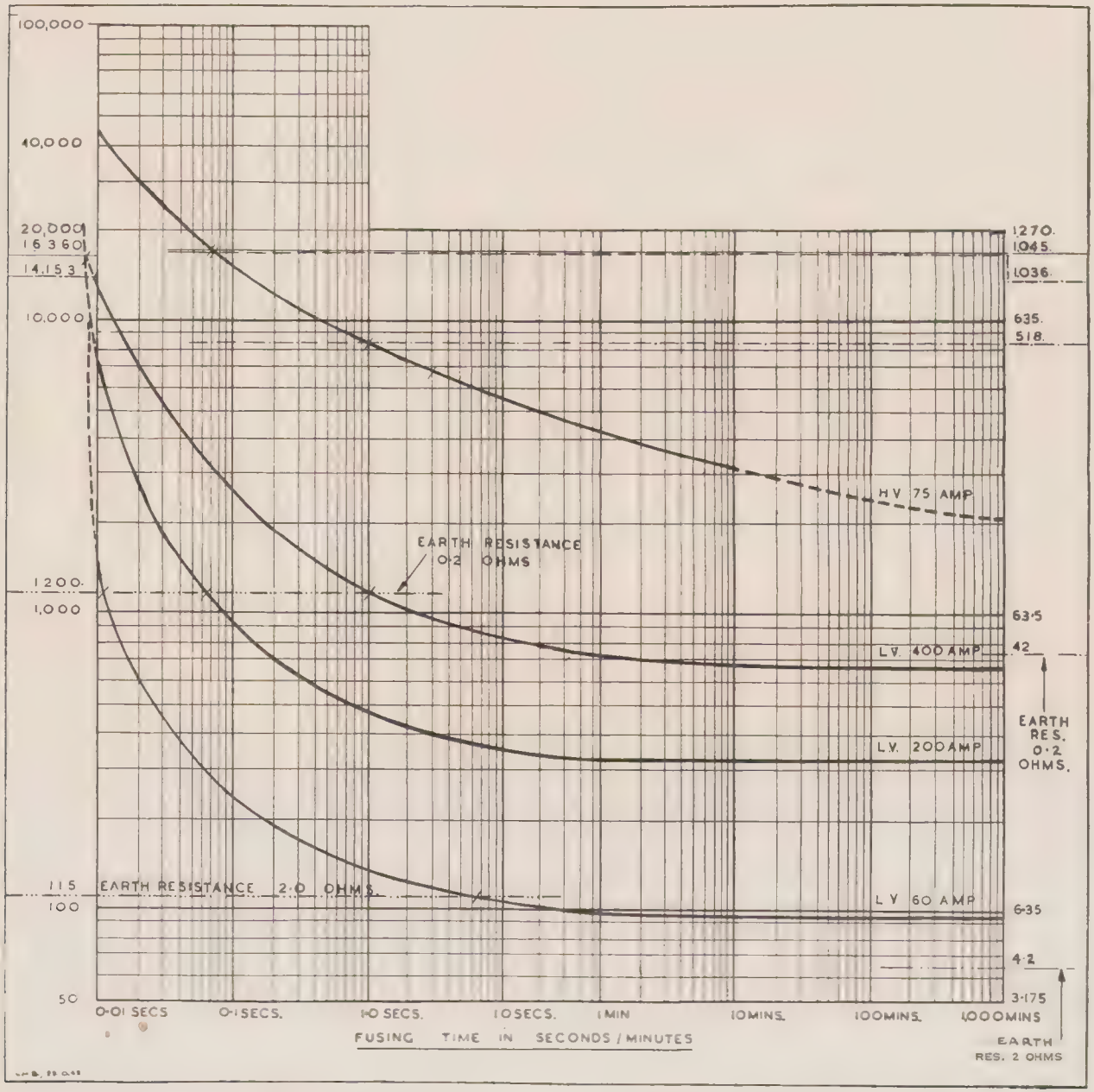


FIG. B-2.

as 231 : 6,300 and the sum of these currents will appear in the third line in an opposite direction. Thus, in the equivalent primary lines, the current will be

$$\frac{231}{6{,}300} \times 14{,}153 = 518\text{·A.}$$

and in the third line 518 × 2 = 1,036 A.



KEY TO FAULT CALCULATIONS — 3 PHASE SYMMETRICAL
LINE TO LINE
LINE TO EARTH

FIG. B-3.

To face page 589

(c) *line to earth fault.*

A line to earth fault short circuits one secondary line. Fault current on the primary side will be confined to primary winding supplying the faulted secondary and will appear in two primary lines. The calculation is as follows :—

Current in primary line A

$$= \frac{-231}{6{,}300} \times (0 - 0) = 0 \text{ A.}$$

Current in primary line B

$$= \frac{-231}{6{,}300} \times (0 - 115) = 4{\cdot}2 \text{ A.}$$

Current in primary line C

$$= \frac{-231}{6{,}300} \times (115 - 0) = -4{\cdot}2 \text{ A.}$$

Reference to Chapter XIII, page 287 should be made for the basis of this calculation, noting also that the minus sign in the result for line C indicates that the current is opposite in direction to that in line B.

The results of the calculations up to this point can now be shown diagrammatically as in Fig. B-2.

From this point too, a study can be made of the operating times of the different fuses and of the degree of discrimination as between l.v. and h.v. fuses. In Fig. B-3 are plotted the characteristic curves of

1. the three sizes of l.v. fuse, namely 60, 200 and 400 amp. to the scale of currents on the *left hand* side, and
2. the 75 amp. h.v. fuse to the scale of currents on the *right hand* side,

the ratio between these two scales being that of the main power transformer.

The values of fault current calculated for the different fault conditions are marked by distinguishing lines and from these we can determine the melting times of the various fuses where operation occurs, the results of our observations being summarised as below :—

Type of Fault	L.V.		H.V.	
	Fault Amps.	Melting Time Seconds	Fault Amps.	Melting Time Seconds
Three-Phase	16,360	0·009 for all sizes	1,045	0·065
Line/Line	14,153	0·009 for all sizes	518 (A & B) 1,036 (C)	1·00 0·07
Line/Earth	115	60A = 6·5 200 A. } not 400 A. } affected	4·2 in lines (C & B)	not affected

A study of the tabulation above shows that

(1) In the case of three-phase and line/line faults, there is a time margin of discrimination between l.v. and h.v. fuses of more than 0·05 seconds, thus ensuring that the h.v. fuses have not melted before total clearance is made by the l.v. fuses.

(2) In the case of line/earth faults, only the 60 amp. l.v. circuit is protected by its fuses, there being insufficiency of current to operate the 200 and 400 amp. fuses.

With an earth fault on either of the larger l.v. circuits therefore, it is clear that this may continue until such time as it is converted into a lower impedance line to line fault. The immediate remedy would be to decrease the value of earth resistance, and we might, for example, assume that instead of 2 ohms., the value is reduced to 0·2 ohms. For all practical purposes, where the value of earth resistance swamps all other impedances, we may use ohm's law to determine the current in the event of an earth fault, dividing the voltage impressed across the resistance by the value of the resistance ; in our first example for instance, 231/2=115·5 A against the figure of 115 previously obtained.

Reducing the earth resistance to 0·2 ohms we get 231/0·2 = 1,155 A., a value ample to cause operation of any one of the three sizes of l.v. fuse, the 60 amp. in 0·01 secs., the 200 amp. in 0·065 secs., and the 400 amp. in 1·0 secs. But with the higher value of l.v. earth fault current we shall obviously have a correspondingly higher value appearing in two of the primary lines, and this clearly will be 10 times our value of 4·2 amp. or 42 amp. Reference to Fig. B-3 will show that such a value will not affect the h.v. 75 amp. fuse.

The problem of obtaining earth fault protection with fuses is one of importance, particularly when using tripping fuses which are claimed to prevent single-phasing, as if the earth resistance is sufficiently high to seriously limit the earth fault current, it is unlikely to cause operation of fuses and as line to earth faults are the most likely cause of single-phasing, the value of the tripping fuse is lost.

One way to approach the problem is to determine the value of earth resistance which will ensure sufficiency of current to melt the largest fuse at some maximum permissible time. Let us assume that we can allow an earth fault to persist for one second. From the time/current curve ascertain the fusing current for the *largest* fuse at one second. In the example used, our 400 amp. fuse has a fusing current of 1,200 amps. at one second. To obtain the maximum earth resistance we then have

$$1{,}200 = \frac{231}{R}$$

so that R = 0·193 ohms.

APPENDIX C

USEFUL DATA

The data in this section is included for convenient reference. Much of it has appeared elsewhere and where necessary acknowledgement to its source is given in brackets.

BUSBARS AND CONNECTIONS

(1) Properties of Copper (Copper Development Association).

Thermal Co-efficient of Linear Expansion	$16{\cdot}6 \times 10^{-6}$ per °C. $9{\cdot}22 \times 10^{-6}$ per °F.
Modulus of Elasticity (Hard Drawn)	18×10^{6} lb. per sq. in.
Modulus of Torsion	$6 - 7 \times 10^{6}$ lb. per sq. in.
Tensile Strength (Hard Drawn) ..	20 — 30 tons per sq. in.
Electrical Resistance of Annealed Copper (I.E.C. Standard per foot per sq. inch section)..	8·1455 microhms at 20°C. 8·0041 microhms at 60°C.
Electrical Resistance of Hard Drawn Copper	$= \text{Ra}\left(1 + \frac{\text{T}}{1{,}000}\right)$

Where Ra = Resistance annealed.
T = Tensile strength hard drawn in tons per sq. inch.

(2) Direct Current Carrying Capacity of the More Frequently Used Copper Conductors (Copper Development Association).

Dimensions	Amperes
1 in. × $\frac{1}{16}$ in.	200
1 in. × $\frac{1}{8}$ in.	290
2 in. × $\frac{1}{8}$ in.	525
1 in. × $\frac{1}{4}$ in.	430
1$\frac{1}{2}$ in. × $\frac{1}{4}$ in.	600
2 in. × $\frac{1}{4}$ in.	760
2$\frac{1}{2}$ in. × $\frac{1}{4}$ in.	920
3 in. × $\frac{1}{4}$ in.	1,080
4 in. × $\frac{1}{4}$ in.	1,380
5 in. × $\frac{1}{4}$ in.	1,680
6 in. × $\frac{1}{4}$ in.	1,970

Based on single conductors mounted horizontally on edge and freely exposed to still air, with a temperature rise of 40°C. above an ambient temperature of 30°C. See also Chapter X for factors for multiple bars and for alternating current ratings.

(3) Properties of Aluminium (British Aluminium Company).

Thermal Co-efficient of Linear Expansion (average value 20°–100°C.) ..	24×10^{-6} per °C.
Modulus of Elasticity	$9{\cdot}9 \times 10^{6}$ lbs. per square inch.
Modulus of Torsion	$3{\cdot}87 \times 10^{6}$ lbs. per square inch.
Tensile Strength (Hard)	9 tons per square inch.
Standard Specific Resistance for H.D. wire at 20°C.	2·845 microhms per cm. cube.
Co-efficient of increase of resistance with temperature for H.D. wire at 15·6°C. (60°F.).	°C. 0·00407. °F. 0·00226.

(4) Direct Current Carrying Capacity of the More Frequently Used Aluminium Conductors (British Aluminium Company).

Aluminium

Dimensions	Amperes Bright	Amperes Dull Black
2 in. × ¼ in.	598	733
2 in. × ⅜ in.	738	905
3 in. × ¼ in.	862	1055
3 in. × ⅜ in.	1055	1290
4 in. × ¼ in.	1125	1380
4 in. × ⅜ in.	1370	1680
5 in. × ¼ in.	1380	1690
5 in. × ⅜ in.	1675	2050
6 in. × ¼ in.	1635	2000
6 in. × ⅜ in.	1980	2425

Above are for single conductors mounted on edge, and based on a 40° rise above 30°C. ambient temperature. Where a 50°C. rise is permissible, capacities can be multiplied by 1·135.

(5) Heating of Conductors for very short periods (as when short-circuited).

For copper conductors:—

$$\theta = 1{\cdot}2 \left(\frac{I}{A}\right)^{2} \cdot 10^{-8}$$

where θ = Temperature Rise per second Deg. C.
A = Sectional Area of Conductor in square inches.
I = Current.

The value 1·2 is a co-efficient for copper. For aluminium the value is 2·8.

Assuming a melting point for copper of 1,084 degree C., the following formula may be used to determine the smallest cross-section to carry a known current for a known time without melting.

$$A = I \times 10^{-6} \times 5{\cdot}24 \sqrt{t}.$$

where A = cross sectional area in square inches.
t = time in seconds.

An example of use for the above formula is that of an earthing conductor used on an installation of high short-circuit capacity.

(6) To obtain resistance of Copper Conductors of known uniform cross-sectional area.

$$\text{Resistance per foot in ohms at } 60°\text{F.} = \frac{8 \times 10^{-6}}{\text{Sect. Area in Sq. Ins.}}$$

This is true for annealed high conductivity copper. For hard-drawn copper conductors, the value will be about 2% higher.

(7) To obtain resistance of Copper Conductors at a higher temperature where the value is known at a lower temperature.

$$R_2 = R_1 (1 + at)$$

where R_2 = Resistance at higher temperature
R_1 = Resistance at lower temperature
t = Temperature Diff. Deg. C.
a = 0·00428.

CABLES AND OVERHEAD LINES

(8) Approximate Resistance, Reactance and Impedance of Multi-core Cables at 50 Cycles (J. & P. Ltd.).

In using the following tables, it is advisable to remember that they show figures representing one cable manufacturer only. For any particular scheme, figures should be obtained from the actual cable maker if possible. The figures given, however, are sufficiently near for most calculations. *All figures are per core per mile and are for circular conductors.*

Approximate Resistance, Reactance and Impedance of Multi-core Cables

Values are per core per mile at 50 cycles.

Std. Size of Cable. Nominal Area in Sq. Ins.	Resistance ohms	Reactance ohms kV				Impedance ohms kV			
		0·66	3·3	6·6	11	0·66	3·3	6·6	11
0·007	6·271	0·15428	—	—	—	6·272	—	—	—
0·01	4·197	0·14596	—	—	—	4·199	—	—	—
0·0145	3·005	0·13983	0·16314	0·18218	—	3·008	3·008	3·009	—
0·0225	1·985	0·13305	0·15356	0·17068	0·19406	1·989	1·991	1·993	1·995
0·03	1·549	0·12912	—	0·16374	0·18574	1·554	—	1·558	1·561
0·04	1·109	0·12478	0·14153	0·15592	0·17621	1·116	1·118	1·119	1·123
0·06	0·7323	0·12013	0·13455	0·14718	0·16531	0·7419	0·7446	0·7469	0·7508
0·075	0·5786	0·11784	0·13104	0·14266	0·15962	0·5905	0·5932	0·5960	0·6002
0·10	0·4354	0·11536	0·12711	0·13770	0·15325	0·4504	0·4536	0·4567	6·4616
0·12	0·3761	0·11410	0·12516	0·13518	0·14998	0·3930	0·3965	0·3997	0·4050
0·15	0·2972	0·11231	0·12243	0·13160	0·14527	0·3176	0·3215	0·3250	0·3308
0·20	0·2237	0·11046	0·11944	0·12764	0·14002	0·2495	0·2536	0·2575	0·2638
0·25	0·1782	0·11049	0·11721	0·12475	0·13622	0·2096	0·2133	0·2175	0·2244
0·30	0·1452	0·10930	—	—	—	0·1818	—	—	—
0·40	0·1082	0·10879	—	—	—	0·1534	—	—	—
0·50	0·08814	0·10773	—	—	—	0·1392	—	—	—

The reactance figures for Sector Conductors are 0·92 of those above for Circular Conductors.

(9) Approximate Resistance, Reactance and Impedance of HD. HC. Copper Conductors—Overhead Lines (J. & P., Ltd.).

The figures below are based on a periodicity of 50 Cycles per second. Values are in ohms per 1,000 yards. Based on H.T. Spacings of three and four feet.

Area Sq. Inches	Stranding	Resistance at 60°F.	Reactance		Impedance	
			3 feet Spacing	4 feet Spacing	3 feet Spacing	4 feet Spacing
0·0201	8 S.W.G.	1·244	0·3654	0·3819	1·296	1·3010
0·0221	7/·064	1·132	0·3587	0·3753	1·1867	1·1924
0·025	3/·104	0·9887	0·3540	0·3705	1·0501	1·0558
0·04	3/·131	0·6227	0·3407	0·3573	0·7098	0·7178
0·05	3/·147	0·4943	0·3340	0·3503	0·5966	0·6031
0·06	3/·161	0·4121	0·3289	0·3454	0·5273	0·5379
0·075	3/·180	0·3294	0·3224	0·3390	0·4611	0·4727
0·1	7/·136	0·2469	0·3156	0·3322	0·4007	0·4139
0·125	7/·152	0·1976	0·3092	0·3257	0·3669	0·3790
0·15	7/·166	0·1656	0·3042	0·3207	0·3463	0·3609

The following figures are for L.T. Spacing, 3-Phase, 4-Wire 50 Cycles in vertical formation at 12-inch Spacing. Values are in ohms per 1,000 yards.

			Reactance	Impedance
0·025	3/·104	0·9887	0·3170	1·0382
0·04	3/·131	0·6227	0·3035	0·6947
0·05	3/·147	0·4943	0·2966	0·5765
0·06	3/·161	0·4121	0·2913	0·5047
0·075	3/.180	0·3294	0·2848	0·4355
0·1	7/·136	0·2469	0·2819	0·3747
0·125	7/·152	0·1976	0·2753	0·3388
0·15	7/.166	0·1656	0·2701	0·3167

(10) Cable or Line Data—Short Circuit Calculations.

To obtain percentage reactance (or resistance) at a given kVA base for ohmic value X (or R),

$$= \frac{100{,}000 \times \text{kVA base} \times \text{X (or R)}}{(\text{Voltage})^2}$$

(11) Reactance of Single Core Cables (W. T. Henley's Telegraph Works, Ltd.).

The following formula may be used to obtain the approximate reactance of single-core cables.

$L = k + 0{\cdot}421 \log_{10} (d/r)$.

where d = centres in inches.

r = radius of conductor in inches.

k = 0·054 for 7 strand cables.
0·0506 for 19 strand cables.
0·0457 for 37 strand cables.

L = Inductance.

and then

$X = 2\pi f L \times 10^{-3}$ ohms per 1,000 yards.

where X = reactance in ohms.

f = frequency.

(12) Zero Phase-Sequence Reactances for overhead lines (Switchgear Handbook, Volume Two).

The following values of zero phase-sequence reactance are for one three-phase line and are approximate only.

With no earth wire	$X_0 = 3{\cdot}5X_1$.
With light steel earth wire	$X_0 = 3{\cdot}5X_1$.
With non-magnetic earth wire	$X_0 = 2X_1$.

where X_1 = positive phase-sequence reactance.

(13) Bending Radii Factors for Paper Insulated Cables (J. & P. Ltd.).

Working Voltage	Type of Cable	Method of Installation			
		Laid Direct	Drawn in Ducts	Adjacent to Joints and Terminations (*a*)	
				With Former	Without Former
Up to and including 11 kV	All Types	10 (b.c.)	10 (b.c.)	8 (c)	8 (c)
22 and 33 kV	3 Core with or without armour	25 (d.e.)	40 (d.e.)	15 (e)	15 (e)
	3 Core S.L.	25 (d.f.)	40 (d.f.)	15 (f)	15 (f)
	Individual Cores of S.L.	—	—	15 (e)	25 (e)
	Single Core	40 (d.e.)	40 (d.e.)	15 (e)	25 (e)
66 kV	All types Single Core	40 (d.e.)	40 (d.e.)	15 (e)	25 (e)

Notes.—(*a*) *It is important to note the smaller permissible factors at joints or terminations.*
(*b*) *During laying 15 times.*
(*c*) *Times the overall diameter of cable.*
(*d*) *If the radius exceeds six feet by using this factor, six feet may be used.*
(*e*) *Times the diameter over lead.*
(*f*) *Times the diameter over armouring.*

ELECTRIC MOTORS

(14) Approximate full load Stator Currents for 3-Phase A.C. Induction Motors.

H.P of Motor	Voltage	
	400 V.	440 V.
	Amperes	Amperes
1	1·8	1·7
2	3·4	3·1
3	4·8	4·4
4	6·4	5·6
5	7·6	6·9
7½	11·0	10·0
10	14·3	13·0
15	21·0	19·0
20	28·0	26·0
25	35·0	32·0
30	41·0	38·0
40	56·0	51·0
50	69·0	63·0
60	83·0	75·0
70	97·0	88·0
80	111·0	101·0
90	124·0	118·0
100	138·0	126·0
150	206·0	187.0
200	274·0	249.0
250	335·0	305.0

The above figures assume average power factor and efficiency.

(15) Fusing Guide for L.V. Motor Starting Circuits.

In all applications where fuses are used for the protection of motors, it is important to appreciate that the fuse serves solely to protect the motor and its cables against short-circuit. Overload protection, if required, must be provided at the motor starter. It is important, too, to remember that the discrimination afforded by the modern hrc Cartridge Fuse can only be obtained by a proper selection of the fuse rating. In the case of steady loads the selection of the fuse rating will depend on characteristics entirely different from those of a motor circuit, and these must, if full value of the protection afforded is to be obtained, be taken into full account.

It has been repeatedly stressed that the extraordinary performance of the hrc fuse can be nullified by haphazard selection of normal rating. Too often is selection made by determining the fuse rating by the maximum rating of the switch or circuit-breaker with which it is associated. This can rarely be described as "selection" and incorrect operation, or lack of operation, can be regularly traced to this method.

Ratings selected from Table A are such that fuses will carry the currents likely to be encountered in normal service but will operate in a minimum of time under fault conditions.

The method of selection is as follows :—

Motor circuits may be divided into three classes of drive. Classes A and B are the most common, and are covered in Table A for squirrel cage, slip ring and D.C. motors, and further sub-divided for type of starter. For squirrel cage motors, the standstill current is required ; for slip ring and D.C. motors, the full load current. Given the data as outlined above, selection is made by reference to the table, as the following example indicates.

Squirrel-Cage Motor.
Type of Drive—A.
Starter—Direct on Line.
Standstill Current = 80 amps.
Nearest higher figure column 1 = 86 amps.
Corresponding Fuse Rating = 50 amps.

If the motor is started more than ten times per hour the standstill current must be multiplied by the factor 1·1, thus :

Standstill Current = 80 amps.
Frequent start factor = 80 × 1·1 = 88 amps.
Nearest higher figure Column 1 = 112 amps.
Corresponding Fuse Rating = 60 amps.

The third class of drive C, requires special consideration and suitable ratings should be ascertained from the fuse maker. The information required is :—

Type of machinery being driven.
Moment of inertia of moving parts.
Type of Motor and Starter.
Full load and Standstill Currents.
Time to run up to speed.
No. of starts per hour.
Ambient temperature.

TABLE A.

Fuse Rating	Type of Motor and Starter					
	Squirrel-Cage Motors				Slip-ring or Direct Current Motors	
	Direct-to-Line Starter		Star-Delta or Auto-transformer Starter		Resistance Starter	
	(1) A	(2) B	(3) A	(4) B	(5) A	(6) B
	Standstill current not in excess of	Standstill current not in excess of	Standstill current not in excess of	Standstill current not in excess of	F.L. current not in excess of	F.L. current not in excess of
amps.	amps.	amps.	amps.	amps.	amps.	amps.
10	17	16·5	23	22·5	4·6	4·5
20	35	33	48	46	9·7	9·1
30	53	50	73	69	14·5	14
40	70	67	97	92	19·5	18·5
50	86	82	119	112	24	22
60	112	103	154	142	31	28
80	164	149	225	205	45	41
100	205	185	280	255	56	51
150	415	370	570	510	114	102
200	600	525	825	725	165	145
250	780	675	1,080	925	215	185
300	950	820	1,310	1,130	265	225
350	1,150	1,020	1,600	1,400	320	280
400	1,350	1,180	1,850	1,620	370	325
450	1,580	1,375	2,200	1,860	435	375
500	1,750	1,470	2,380	2,020	475	405
600	2,100	1,820	2,900	2,500	580	500
700	2,550	2,130	3,500	2,950	700	590
750	2,850	2,400	3,950	3,300	750	665
800	3,100	2,600	4,250	3,550	800	710

A = Normal industrial drives with starting time not exceeding 12 seconds, e.g. light or medium machine tools, presses, industrial machinery.

B = Drives with heavy inertia, starting time not exceeding 30 seconds, e.g. induced and forced draught fans, blowers, centrifuges.

(16) A Useful Formula for calculating Stator Currents for Three-Phase Motors is:—

Up to and including 5 B.H.P. :— $C = \frac{600\ (\text{B.H.P.} + 0{\cdot}30)}{\text{volts}}$

From 5 B.H.P. to 30 B.H.P. :— $C = \frac{540\ (\text{B.H.P.} + 0{\cdot}90)}{\text{volts}}$

Above 30 B.H.P. :— $C = \frac{520\ (\text{B.H.P.} + 2{\cdot}10)}{\text{volts}}$

INSULATION

(17) Schedule of Physical Properties of Insulating Oils (B.S.S. 148).

Class of Oil	Sludge (Max.)	Viscosity at 15·5°C. (Max.)	Electric Strength (Min.)	Flash Point (Min.)	Cold Test (Max.)
	Per Cent.	Redwood Seconds	Volts		
A.0	0·1	200	30,000	145°C. (293°F.)	0°C. (32°F.)
A.10					−10°C. (14°F.)
A.30					−30°C. (−22°F.)
B·0	0·8	200	30,000	145°C. (293°F.)	0°C. (32°F.)
B.10					−10°C. (14°F.)
B.30					−30°C. (−22°F.)

Class A oil may be termed non-sludging and is suitable for use in oil circuit breakers where the working temperature exceeds 70°C. (158°F.). Recommended for all breakers above 500 ampere rating.

Class B oil for general use in circuit breakers outside the conditions demanding Class A.

For unusually cold situations A.30 or B.30 oil should be used.

(18) Table of Dielectric Constants and Electric Strengths (Calculation and Design of Electrical Apparatus).

Insulating Material	Dielectric Constant		Electric Strength volts per mil.	
	Range †	Typical or mean value	Range †	Typical or mean value
Air*	1·0	1·0	69– 79	76
Bakelite	3·6–8·8	5·0	560	560
Bakelite Mouldings	4·5–7·0	5·7	200– 560	380
Compound Semi-Solid	2·5–3·0	2·8	450– 600	500
Compound Semi-Fluid....	2·3–2·6	2·4	300– 400	350
Oil, Transformer	2·2–2·5	2·4	250	250
Paper, dry	1·7–2·6	2·4	200– 350	275
Paper, oiled	2·6–3·8	3·5	500–1500	550
Paper, bakelised	5·0–5·6	5·2	400–1500	750
Porcelain	4·4–6·8	4·8	220– 300	240
Rubber, pure	1·8–2·6	2·3	100– 250	175
Rubber, vulcanised	2·6–2·9	2·7	300– 700	500
Rubber, hard	3·0	3·0	750–1500	1120
Shellac	2·7–3·8	3·2	400– 580	500
Slate	6·0–7·0	6·8	5– 10	6

**At about 760 m/m. pressure. Other gases have a dielectric constant within 1 per cent. of unity.*

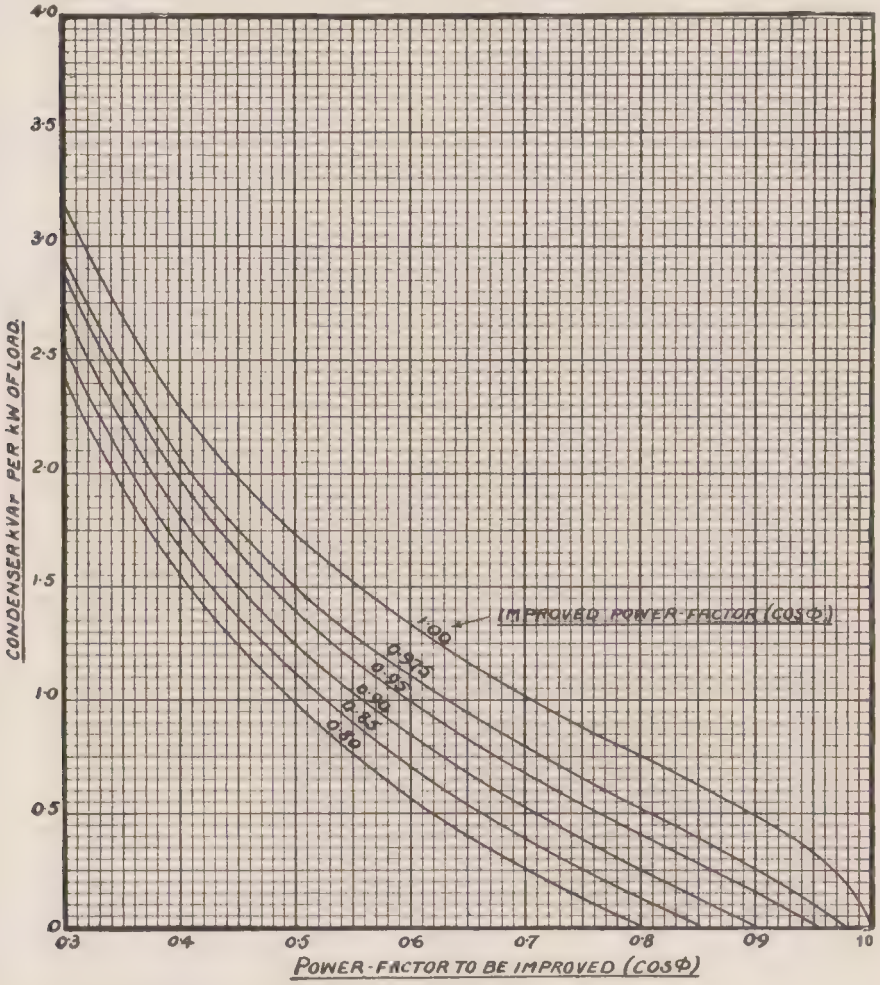
†Variation due to classes of insulation comprising families of substances with non-identical characteristics and due to fact that electric strength usually decreases considerably with thickness.

POWER FACTOR CORRECTION

(19) Power Factor Correction.

Many of the Engineers who will use this book will be those whose responsibilities include factory equipment as a whole, probably including power factor correction equipment.

For this reason the following chart has been included from which the condenser kVAr per kW of load may be determined.



The procedure in using this chart is :—

The abscissa scale is scaled in uncorrected power factor of the load.

The ordinate scale is scaled in condenser kVAr per kW of load.

With a knowledge of the existing load power-factor, trace a line upwards from the appropriate point on the abscissa scale to intersect the curve marked with the desired power factor. By reading off horizontal scale, obtain the value of condenser kVAr per kW of load. Intermediate values of improved power-factor can be estimated with a fair degree of accuracy.

Example :—

Load .. = 500 kW Required P.F. .. .. = 0·95 lagging

Present P.F. = 0·7 lagging Condenser kVAr per kW = 0·68

Total Condenser kVAr = 500 × 0·68 = 340 kVAr.

INSTRUMENTS AND RELAYS

(20) Representative Burdens of Instruments, Meters and Relays.

The following table gives details of the burdens due to various types and makes of indicating and integrating meter, and of relays, the maker's name and type being given.

Manufacturer	Type of Instrument		Movement	Ref.	Dial	Each Current Coil			Each Voltage Coil			Remarks (Res. if required)
						Amps.	V.A.	Watts	Volts	V.A.	Watts	
Johnson & Phillips, Ltd.	Ammeter	Switchboard	Hot wire		8″	5	1·6		—	—	—	
	,,	,,	M.I.		,,	5	3·6		—	—	—	
	,,	,,	Indn.		,,	5	3·2		—	—	—	
	,,	,,	M.I.	MH4	4″	1	3		—	—	—	
	Voltmeter	,,	Hot wire		8″	—	—	—	110	2·0		
	,,	,,	M.I.		,,	—	—	—	110	5·6		
	,,	,,	Indn.		,,	—	—	—	110	10·9		
	Frequency Meter	,,	Reed		,,	—	—	—	110	4		
Metropolitan Vickers, Ltd.	Ammeter	Miniature Control Board	M.I.	S.L.	3½″	1	4	3·5	—	—	—	
	,,	,,	,,	,,	,,	5	3	2·7	—	—	—	
	,, (Low Energy)	,,	,,	,,	,,	1	1	0·9	—	—	—	
	,, ,, ,,	,,	,,	,,	,,	5	·65	·55	—	—	—	
	Voltmeter	,,	,,	,,	,,	—	—	—	110	6	—	
	,, (Low Energy)	,,	,,	,,	,,	—	—	—	110	2	—	
	P.F.I. Single Phase	,,	Indn.	F.C.	,,	1	14	5	110	5·5	5·5	
	,, ,, ,,	,,	,,	,,	,,	5	11	4	110	5·5	5·5	
	,, Three ,,	,,	,,	,,	,,	1	1·2	1·2	110	5·5	5·5	3 Current Coils

Manufacturer	Type of Instrument		Movement	Ref.	Dial	Each Current Coil			Each Voltage Coil			Remarks (Res. if required)
						Amps.	V.A.	Watts	Volts	V.A.	Watts	
Metropolitan Vickers, Ltd. —cont'd	P.F.I. Three Phase	Miniature Control Board	Indn.	F.C.	3½"	5	1	1	110	5·5	5·5	3 Current Coils
	Wattr. Single Phase	,,	Dyn.	,,	,,	1	2·5	2·5	110	3·5	1·1	
	,, ,, ,,	,,	,,	,,	,,	5	2	2	110	3·5	1·1	
	,, Three ,,	,,	,,	,,	,,	1	2·5	2·5	110	3·5	1·1	2 Current Coils
	,, ,, ,,	,,	,,	,,	,,	5	2	2	110	3·5	1·1	2 Current Coils
	Ammeter	Switchboard	M.I.	S.L.	8"	5	2–3*	1·8–2·7*	—	—	—	*According to Range
	,, (Low Energy)	,,	,,	,,	,,	5	·55–·65*	·47–·55*	—	—	—	* ,, ,, ,,
	Voltmeter	,,	,,	,,	,,	—	—	—	110	6·0–7·5*	6·0–7·5*	* ,, ,, ,,
	,, (Low Energy)	,,	,,	,,	,,	—	—	—	110	1·7–2·2*	1·7–2·2*	* ,, ,, ,,
	P.F.I. Single Phase	,,	Indn.	F.C.	6" & 8"	5	11	4	110	5·5	5·5	
	,, Three ,,	,,	,,	,,	,,	5	1	1	110	5·5	5·5	
	Wattr. Single Phase	,,	,,	,,	6" & 8"	5	2	2	110	3·5	1·1	
	,, Three ,,	,,	,,	,,	8"	5	2	2	110	3·5	1·1	
	Frequency Meter	,,	,,	,,	6" & 8"	—	—	—	110	15	9	2 Current Coils, 2 Volt Coils
	Synchroscope	,,	Dyn.	,,	6" 8" 12" 18" & 24"	—	—	—	110	14	10	Busbar Side
									110	14	13	Machine Side
	Watthour Meter 1 PH	,,	Indn.	N.E.1	—	5	1	0·8	110	6	1·2	1 Current Coil 1 Volt Coil
	,, ,, 2 PH, 3W	,,	,,	NE	—	5	1	0·8	110	6	1·2	2 Current Coils, 2 Volt Coils
	,, ,, 3 PH, 3W	,,	,,	,,	—	5	1	0·8	110	6	1·2	2 Current Coils, 2 Volt Coils
	Instantaneous Relay	Non-Dir.	Att. Arm	FR-M	—	·5	6·25	6	—	—	—	M/C Protection
						·3	0·77	PF. 1·0 App	—	—	—	Transr. Protection, Res. reqd.
	,, ,,	,,	,,	FG	—	·5	0·33	PF. 0·14	—	—	—	Forms L M & U
	,, ,,	,,	,,	FX	—	·5	1·0	PF. 0·14	—	—	—	
	,, ,,	,,	,,	FW	—	·5	1·0	PF. 0·14	—	—	—	

Manufacturer	Type of Instrument		Movement	Ref.	Dial	Each Current Coil			Each Voltage Coil			Remarks (Res. if required)
						Amps.	V.A.	Watts	Volts	V.A.	Watts	
Metropolitan Vickers, Ltd. —cont'd	PF. Regulating Relay		Indn.	NJ	—	5	13	1·8	110	3·8	3·5	Reactive Element
			Motor Element				15	2				Top Electro-Magnet
			Motor Element						110		25	Bottom Electro Magnet inc. Extl. Res. varies with Volts
	O/L & E/L Relays	Non-Dir.	Indn.	PBO	—	5*	2·71*	0·175*	—	—	—	*Values given are for standard 5A, 50–200% Relay, and will vary according to plug setting
	,, ,, ,,	Directional	,,	NPO	—	5*	3·49*	0·36*	110	19	3	
	Reverse Power Relay	,,	,,	NA, NB	—	5*	2·5–0·36*	2·2	—	—	—	*According to Plug Setting
	Phase Balance Relay	Non-Dir.	,,	PXC	—	5	15	10	—	—	—	Red Phase
						5	5	4·5	—	—	—	Blue Phase
	Translay Relay 1 PH		,,	H	—	5	3	2·4	—	—	—	R to Y or Y to B
						2	2·5	2	—	—	—	B to N
	,, ,, 3 PH			HHTA	—	5	12	6	—	—	—	R to N, Y to N, B to N
Nalder Bros. & Thompson	Ammeter	Switchboard	MI	Ideal	6″ & 8″	5	2	1	—	—	—	
	Voltmeter	,,	,,	,,	,,	—	—	—	110	5	4·8	
	P.F.I. 1 PH	,,	,,	,,	,,	5	4·4	4	110	9	6	
	,, 3 PH	,,	,,	,,	,,	5	4·4	4	110	2	1·9	Bald.–1C. & 3V. Coils
	,, 3 PH	,,	,,	,,	,,	5	1·75	1·65	110	5·9	5·7	Bald.–3C. & 1V. Coil
	,, 3 PH	,,	,,	,,	,,	5	1·6	1·5	110	6	5·8	Unbalanced
	Indg. Wattr. 1 PH	,,	Indn.	,,	6″ & 8″	5	2	1·6	110	4·5	3	Single Element
	,, ,, 3 PH. 3 W	,,	,,	,,	,,	5	2	1·6	110	4·5	3	Unbald. Load, 2 Element
	,, ,, 3 PH. 4 W	,,	,,	,,	,,	5	3·5	2·5	110	4·5	3	3 Element
	Synchroscope	,,	MI	Type A	,,	—	—	—	110	11	8	
	Frequency Meter	,,	Indn.	Form F	,,	—	—	—	110	12	6·6	

Manufacturer	Type of Instrument		Movement	Ref.	Dial	Each Current Coil			Each Voltage Coil			Remarks (Res. if required)
						Amps.	V.A.	Watts	Volts	V.A.	Watts	
Nalder Bros. & Thompson —cont'd.	E/L Relay (Instant.)		Att.Arm.	B	—	0·75	0·75	0·5	—	—	—	Single Setting
						0·5	0·375	0·092	—	—	—	Standard 1 am. relay with Variable Setting 0·5–1·5 amps.
						1·0	1·5	0·37	—	—	—	
						1·5	3·375	0·832	—	—	—	
	O/L Relay	0–1 Sec.	Indn.	LB		5	1	0·75	—	—	—	
	,, ,,	0–2 ,,	,,	LC	—	5	2	1·5	—	—	—	
	,, ,,	0–3 ,,	,,	LD	—	5	3	2·2	—	—	—	
	E/L Relay	0–1 ,,	,,	LB	—	5	1	0·75	—	—	—	
	,, ,,	0–2 ,,	,,	LC	—	5	2	1·5	—	—	—	
	,, ,,	0–3 ,,	,,	LD	—	5	3	2·2	—	—	—	
Ferranti	KWh Meter 1 PH. 2 W.	Unbald. Load	Indn.	"FL"	—	5	0·5	0·5	110		1·1	1 C. & 1 V. Coil
	,, ,, 3 PH. 3 W.	,,	,,	"FLY"	—	5	0·4	0·4	110	2	0·8	2 C. & 2 V. Coils
	,, ,, 3 PH. 4 W.	,,	,,	"FLX"	—	5	0·4	0·4	110	2	0·5	3 C. & 3 V. Coils
	RKVAh Meter 3 PH .3 W.	,,	,,	"FLF"	—	5	1·0	1·0	110	6	1·5	2 C. & 2 V. Coils
	,, ,, 3 PH. 4 W.		,,	"FLF"	—	5	1·0	1·0	110	6	1·5	2 C. & 2 V. Coils
	KVAh Meter 3 PH. 3 W.		,,	"FLF"	—	5	1·0	1·0	110	6	1·5	2 C. & 2 V. Coils
	*,, ,, 3 PH. 4 W.		,,	"FLF"	—	5	1·0	1·0	110	6	1·5	2 C. & 2 V. Coils
	**MDI Resetting Coil	—	—	—	—	—	—	—	110	3	2	
	Quadrature Transr.	—	—	—	—	5	10/Phase	3	—	—	—	
	O/L & E/L Relay	Non-Directl.	Indn.	"ON"	—	5	0	2 appx***	—	—	—	***P.F.=0.9
	O/L & E/L Relay	Directional.	,,	"OD"	—	5	2		110	8	3 App	

NOTES.

*i. QUADRATURE TRANSR.—The two element "FLF" 3 Phase 4 Wire Meter has to be used in conjunction with a Quadrature Current Transr. for RKVAh work otherwise it is not satisfactory.

ii. FLF METER.—This is a 2-Element Meter and when metering on 4 Wire Supply it has to be connected to delta connected Current Transformers.

**iii. MDI RESETTING COIL.—Usually only in circuit for about 3 seconds.

Manufacturer	Type of Instrument	Move-ment	Ref.	Dial	Each Current Coil		Each Voltage Coil			Remarks (Res. if required)
					Amps.	V.A.	Watts	Volts	V.A.	Watts	
Landis & Gyr	KWh. Meter 1 PH. 2 W.	Indn.	" C.F.6 "	—	5	0·185	0·15	110	4·3	1·2	1 Element
	" " 2 PH. 3 W.	"	" K.F.3 "	—	5	0·20	0·16	110	4·3	1·2	Lower Element
					5	0·25	0·21	110	4·3	1·2	Upper Element
	" " 3 PH. 3 W.	"	" F.F.3 "	—	5	0·20	0·16	110	4·3	1·2	Lower Element
					5	0·25	0·21	110	4·3	1·2	Upper Element
	" " 3 PH. 4 W.	"	" M.F.3 "	—	5	0·20	0·17	110	4·3	1·2	Lower Element
					5	0·235	0·20	110	4·3	1·2	Middle Element
					5	0·26	0·22	110	4·3	1·2	Upper Element
	RKVAh Meter 1 PH. 2 W.	"	" CF.1ϕ "	—	5	0·54	0·51	110	2·8	2·5	1 Element
	" " 2 PH. 3 W.	"	" KF.1ϕ "	—	5	0·48	0·45	110	2·8	2·5	Lower Element
					5	0·50	0·47	110	2·8	2·5	Upper Element
	" " 3 PH. 3 W.	"	" FF.1ϕ "	—	5	0·48	0·45	110	2·8	2·5	Lower Element
					5	0·50	0·47	110	2·8	2·5	Upper Element
	" " 3 PH. 4 W.	"	" MF.1ϕ "	—	5	0·50	0·47	110	2·8	2·5	Lower Element
					5	0·55	0·52	110	2·8	2·5	Middle Element
					5	0·55	0·53	110	2·8	2·5	Upper Element
	KVAh Meter 2 PH. 3 W.	"	"KF Trivr"	—	5	1·35	1·21	110	6·3	3·8	Lower Element
					5	1·35	1·25	110	6·3	3·8	Upper Element
	" " 3 PH. 3 W.	"	"FF. Trivr"	—	5	1·35	1·21	110	6·3	3·8	Lower Element
					5	1·35	1·25	110	6·3	3·8	Upper Element
	" " 3 PH. 4 W.	"	"MF. Trivr"	—	5	0·75	0·68	110	6·3	3·8	Lower Element
					5	0·82	0·70	110	6·3	3·8	Middle Element

Manufacturer	Type of Instrument		Move-ment	Ref.	Dial	Each Current Coil			Each Voltage Coil			Remarks (Res. if required)
						Amps.	V.A.	Watts	Volts	V.A.	Watts	
Landis & Gyr—cont'd	M.D.I. Operating Coil		"a"	"m"	—	5 —	0·80 —	0·72 —	110 110	6·3 1·6	3·8 0·7	Upper Element Note (i) "b" must be added to "a," where used
	" " Motor	Synchronous	"b" "c"	"mye" "my"	—	— —	— —	— —	110 110	2·0 2·0	1·8 1·8	(ii) Burdens are SPH cond. R.Y—3 W, RN—4 W.
	" " "	Escapement	"d"	"mw"	—	—	—	—	110	2·5	1·5	
Reyrolle	O/L & E/L Relay	Non-Direct.	Indn.	"TJY"	—	5	3·0*	1·1**	—	—	—	*At all settings **At 100% setting
	" " "	Directional	"	"TJEY"	—	4	4·0*	1·5**	110	12		*At all settings **At 100% setting
	Sensitive Relay—E/L etc.	—	"	"RS"	—	35·80 MA	0·03*	0·025*	—	—	—	*At 40 MA setting
	O/L & E/L etc.	—	Att Arm.	"Q"	—	3–15	10*	1·05*	—	—	—	*At minimum setting
	Sensitive Relay—E/L etc.	—	"	"W"	—	0·05–1 0·1–0·2	0·25*	0·016*	—	—	—	*At minimum setting
				"W"	—	0·5–1·0 1·0–2·0	0·375*	0·08*	—	—	—	*At minimum setting
Elliot Bros.	Ammeter		M.I. "	"SIB" "MIB"	8"	5	2·5	PF 0·98	—	—	—	
	Voltmeter		"	"SIB" "MIB"	8"	—	—	—	110	5	PF 0·985	
Price & Belsham	Ammeter	Switchboard	Thermal	"RL"		5	5–5·5	Unity PF	—	—	—	

MISCELLANEOUS

(21) Fractions and Decimals of an Inch.

Fraction	Decimal	Millimetres	Nearest S.W.G. No.	
			No.	Inch
1/64	0·015625	0·3969	28	0·0148
			27	0·0164
1/32	0·03125	0·7937	21	0·032
1/16	0·0625	1·5875	16	0·064
3/32	0·09375	2·3812	13	0·092
1/8	0·125	3·1750	10	0·128
5/32	0·15625	3·9688	8	0·160
3/16	0·1875	4·7625	6	0·192
7/32	0·21875	5·5563	5	0·212
1/4	0·25	6·35	3	0·252
9/32	0·28125	7·1438	2	0·276
5/16	0·3125	7·9375	1	0·300
11/32	0·34375	8·7313	2/0	0·348
3/8	0·375	9·5250	3/0	0·372
13/32	0·40625	10·3188	4/0	0·400
7/16	0·4375	11·1125	5/0	0·432
15/32	0·46875	11·9063	6/0	0·464
1/2	0·5	12·7	7/0	0·5
17/32	0·53125	13·4938		
9/16	0·5625	14·2875		
19/32	0·59375	15·0813		
5/8	0·625	15·875		
21/32	0·65625	16·6688		
11/16	0·6875	17·4625		
23/32	0·71875	18·2563		
3/4	0·75	19·05		
25/32	0·78125	19·8438		
13/16	0·8125	20·6375		
27/32	0·84375	21·4313		
7/8	0·875	22·225		
29/32	0·90625	23·0188		
15/16	0·9375	23·8125		
31/32	0·96875	24·6063		

(22) A Table of Logarithms and Antilogarithms.

Logarithms.

	0	1	2	3	4	5	6	7	8	9	1 2 3	4 5 6	7 8 9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4 8 12	17 21 25	29 33 37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4 8 11	15 19 23	26 30 34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3 7 10	14 17 21	24 28 31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3 6 10	13 16 19	23 26 29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3 6 9	12 15 18	21 24 27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3 6 8	11 14 17	20 22 25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3 5 8	11 13 16	18 21 24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2 5 7	10 12 15	17 20 22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2 5 7	9 12 14	16 19 21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2 4 7	9 11 13	16 18 20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2 4 6	8 11 13	15 17 19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2 4 6	8 10 12	14 16 18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2 4 6	8 10 12	14 15 17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2 4 6	7 9 11	13 15 17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2 4 5	7 9 11	12 14 16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2 3 5	7 9 10	12 14 15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2 3 5	7 8 10	11 13 15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2 3 5	6 8 9	11 13 14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2 3 5	6 8 9	11 12 14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1 3 4	6 7 9	10 12 13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1 3 4	6 7 9	10 11 13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1 3 4	6 7 8	10 11 12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1 3 4	5 7 8	9 11 12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1 3 4	5 6 8	9 10 12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1 3 4	5 6 8	9 10 11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1 2 4	5 6 7	9 10 11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1 2 4	5 6 7	8 10 11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1 2 3	5 6 7	8 9 10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1 2 3	5 6 7	8 9 10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1 2 3	4 5 7	8 9 10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1 2 3	4 5 6	8 9 10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1 2 3	4 5 6	7 8 9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1 2 3	4 5 6	7 8 9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1 2 3	4 5 6	7 8 9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1 2 3	4 5 6	7 8 9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1 2 3	4 5 6	7 8 9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1 2 3	4 5 6	7 7 8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1 2 3	4 5 5	6 7 8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1 2 3	4 4 5	6 7 8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1 2 3	4 4 5	6 7 8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1 2 3	3 4 5	6 7 8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1 2 3	3 4 5	6 7 8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1 2 2	3 4 5	6 7 7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1 2 2	3 4 5	6 6 7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1 2 2	3 4 5	6 6 7

(22) CONTD.

Logarithms.

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7541	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9753	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

To convert common to hyperbolic logs, multiply by 2·3026.

(22) CONTD.

Antilogarithms.

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
·00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1	1	2	2	2
·01	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1	1	2	2	2
·02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1	1	2	2	2
·03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1	1	2	2	2
·04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1	2	2	2	2
·05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1	2	2	2	2
·06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1	2	2	2	2
·07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1	2	2	2	3
·08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1	2	2	2	3
·09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1	2	2	2	2
·10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1	2	2	2	3
·11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2	2	2	2	3
·12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2	2	2	2	3
·13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2	2	2	3	3
·14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2	2	2	3	3
·15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2	2	2	3	3
·16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2	2	2	3	3
·17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2	2	2	3	3
·18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545	0	1	1	1	2	2	2	3	3
·19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2	2	3	3	3
·20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2	2	3	3	3
·21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	2	2	2	3	3	3
·22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2	2	3	3	3
·23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2	2	3	3	4
·24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2	2	3	3	4
·25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2	2	3	3	4
·26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858	0	1	1	2	2	3	3	3	4
·27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2	3	3	3	4
·28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2	3	3	4	4
·29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2	3	3	4	4
·30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2	3	3	4	4
·31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2	3	3	4	4
·32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2	3	3	4	4
·33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2	3	3	4	4
·34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3	3	4	4	5
·35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3	3	4	4	5
·36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3	3	4	4	5
·37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3	3	4	4	5
·38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3	3	4	4	5
·39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3	3	4	5	5
·40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3	4	4	5	5
·41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3	4	4	5	5
·42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3	4	4	5	6
·43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	3	3	4	4	5	6
·44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812	1	1	2	3	3	4	4	5	6
·45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3	4	5	5	6
·46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3	4	5	5	6
·47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3	4	5	5	6
·48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	4	4	5	6	6
·49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4	4	5	6	6

(22) CONTD.

Antilogarithms.

	0	1	2	3	4	5	6	7	8	9	1 2 3	4 5 6	7 8 9
·50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1 1 2	3 4 4	5 6 7
·51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304	1 2 2	3 4 5	5 6 7
·52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1 2 2	3 4 5	5 6 7
·53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1 2 2	3 4 5	6 6 7
·54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1 2 2	3 4 5	6 6 7
·55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1 2 2	3 4 5	6 7 7
·56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1 2 3	3 4 5	6 7 8
·57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793	1 2 3	3 4	6 7 8
·58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1 2 3	4 4	6 7 8
·59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1 2 3	4 5 5	6 7 8
·60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1 2 3	4 5 6	6 7 8
·61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1 2 3	4 5 6	7 8 9
·62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1 2 3	4 5 6	7 8 9
·63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1 2 3	4 5 6	7 8 9
·64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1 2 3	4 5 6	7 8 9
·65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1 2 3	4 5 6	7 8 9
·66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1 2 3	4 5 6	7 9 10
·67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1 2 3	4 5 7	8 9 10
·88	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1 2 3	4 6 7	8 9 10
·69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1 2 3	5 6 7	8 9 10
·70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1 2 4	5 6 7	8 9 11
·71	5129	5140	5152	5164	5176	5188	5200	5212	522	5236	1 2 4	5 6 7	8 10 11
·72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1 2 4	5 6 7	9 10 11
·73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1 3 4	5 6 8	9 10 11
·74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1 3 4	5 6 8	9 10 12
·75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1 3 4	5 7 8	9 10 12
·76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1 3 4	5 7 8	9 11 12
·77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012	1 3 4	5 7 8	10 11 12
·78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1 3 4	6 7 8	10 11 13
·79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1 3 4	6 7 9	10 11 13
·80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1 3 4	6 7 9	10 12 13
·81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2 3 5	6 8 9	11 12 14
·82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2 3 5	6 8 9	11 12 14
·83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2 3 5	6 8 9	11 13 14
·84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2 3 5	6 8 10	11 13 15
·85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2 3 5	7 8 10	12 13 15
·86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2 3 5	7 8 10	12 13 15
·87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2 3 5	7 9 10	12 14 16
·88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2 4 5	7 9 11	12 14 16
·89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2 4 5	7 9 11	13 14 16
·90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2 4 6	7 9 11	13 15 17
·91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2 4 6	8 9 11	13 15 17
·92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2 4 6	8 10 12	14 15 17
·93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2 4 6	8 10 12	14 16 18
·94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2 4 6	8 10 12	14 16 18
·95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2 4 6	8 10 12	15 17 19
·96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2 4 6	8 11 13	15 17 19
·97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2 4 7	9 11 13	15 17 20
·98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2 4 7	9 11 13	16 18 20
·99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2 5 7	9 11 14	16 18 20

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(23) A Table of Chords, Sines, Cosines, Tangents, etc.

Angle		Chords	Sine	Tangent	Cotangent	Cosine			
Deg.	Radians								
0°	0	0	0	0	∞	1	1·414	1·5708	90°
1	0·0175	0·017	0·0175	0·0175	57·2900	0·9998	1·402	1·5533	89
2	0·0349	0·035	0·0349	0·0349	28·6363	0·9994	1·389	1·5359	88
3	0·0524	0·052	0·0523	0·0524	19·0811	0·9986	1·377	1·5184	87
4	0·0698	0·070	0·0698	0·0699	14·3007	0·9976	1·364	1·5010	86
5	0·0873	0·087	0·0872	0·0875	11·4301	0·9962	1·351	1·4835	85
6	0·1047	0·105	0·1045	0·1051	9·5144	0·9945	1·328	1·4661	84
7	0·1222	0·122	0·1219	0·1228	8·1443	0·9925	1·325	1·4486	83
8	0·1396	0·139	0·1392	0·1405	7·1154	0·9903	1·312	1·4312	82
9	0·1571	0·157	0·1564	0·1584	6·3138	0·9877	1·299	1·4137	81
10	0·1745	0·174	0·1736	0·1763	5·6713	0·9848	1·286	1·3963	80
11	0·1920	0·192	0·1908	0·1944	5·1446	0·9816	1·272	1·3788	79
12	0·2094	0·209	0·2079	0·2126	4·7046	0·9781	1·259	1·3614	78
13	0·2269	0·226	0·2250	0·2309	4·3315	0·9744	1·245	1·3439	77
14	0·2443	0·244	0·2419	0·2493	4·0108	0·9703	1·231	1·3265	76
15	0·2618	0·261	0·2588	0·2679	3·7321	0·9659	1·217	1·3090	75
16	0·2793	0·278	0·2756	0·2867	3·4874	0·9613	1·204	1·2915	74
17	0·2967	0·296	0·2924	0·3057	3·2709	0·9563	1·190	1·2741	73
18	0·3142	0·313	0·3090	0·3249	3·0777	0·9511	1·176	1·2566	72
19	0·3316	0·330	0·3256	0·3443	2·9042	0·9455	1·161	1·2392	71
20	0·3491	0·347	0·3420	0·3640	2·7475	0·9397	1·147	1·2217	70
21	0·3665	0·364	0·3584	0·3839	2·6051	0·9336	1·133	1·2043	69
22	0·3840	0·382	0·3746	0·4040	2·4751	0·9272	1·118	1·1868	68
23	0·4014	0·399	0·3907	0·4245	2·3559	0·9205	1·104	1·1694	67
24	0·4189	0·416	0·4067	0·4452	2·2460	0·9135	1·089	1·1519	66
25	0·4363	0·433	0·4226	0·4663	2·1445	0·9063	1·075	1·1345	65
26	0·4538	0·450	0·4384	0·4877	2·0503	0·8988	1·060	1·1170	64
27	0·4712	0·467	0·4540	0·5095	1·9626	0·8910	1·045	1·0996	63
28	0·4887	0·484	0·4695	0·5317	1·8807	0·8829	1·030	1·0821	62
29	0·5061	0·501	0·4848	0·5543	1·8040	0·8746	1·015	1·0647	61
30	0·5236	0·518	0·5000	0·5774	1·7321	0·8660	1·000	1·0472	60
31	0·5411	0·534	0·5150	0·6009	1·6643	0·8572	0·985	1·0297	59
32	0·5585	0·551	0·5299	0·6249	1·6003	0·8480	0·970	1·0123	58
33	0·5760	0·568	0·5446	0·6494	1·5399	0·8387	0·954	0·9948	57
34	0·5934	0·585	0·5592	0·6745	1·4826	0·8290	0·939	0·9774	56
35	0·6109	0·601	0·5736	0·7002	1·4281	0·8192	0·923	0·9599	55
36	0·6283	0·618	0·5878	0·7265	1·3764	0·8090	0·908	0·9425	54
37	0·6458	0·635	0·6018	0·7536	1·3270	0·7986	0·892	0·9250	53
38	0·6632	0·651	0·6157	0·7813	1·2799	0·7880	0·877	0·9076	52
39	0·6807	0·668	0·6293	0·8098	1·2349	0·7771	0·861	0·8901	51
40	0·6981	0·684	0·6428	0·8391	1·1918	0·7660	0·845	0·8727	50
41	0·7156	0·700	0·6561	0·8963	1·1504	0·7547	0·829	0·8552	49
42	0·7330	0·717	0·6691	0·9004	1·1106	0·7431	0·813	0·8378	48
43	0·7505	0·733	0·6820	0·9325	1·0724	0·7314	0·797	0·8203	47
44	0·7679	0·749	0·6947	0·9657	1·0355	0·7193	0·781	0·8029	46
45	0·7854	0·765	0·7071	1·0000	1·0000	0·7071	0·965	0·7854	45
			Cosine	Cotangent	Tangent	Sine	Chords	Radians	Deg.
								Angle	

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(24) Fuse Wire Table.

Fusing Current Amps.	Copper		Aluminium		Tin		Allo-Tin		Lead	
	Diam. Ins.	S.W.G. Approx.	Diam. Ins.	S.W.G. Approx.	Diam. Ins.	S.W.G. Approx.	Diam. Ins.	S.W.G. Approx.	Diam. Ins.	S.W.G. Approx.
1	0·0021	47	0·0026	46	0·0072	37	0·0083	35	0·0081	35
2	0·0034	43	0·0041	42	0·0113	31	0·0132	29	0·0128	30
3	0·0044	41	0·0054	39	0·0149	28	0·0173	27	0·0168	27
4	0·0053	39	0·0065	37	0·0181	26	0·0210	25	0·0203	25
5	0·0062	38	0·0076	36	0·0210	25	0·0243	23	0·0236	23
10	0·0098	33	0·0120	30	0·0334	21	0·0386	19	0·0375	20
15	0·0129	30	0·0158	28	0·0437	19	0·0506	18	0·0491	18
20	0·0156	28	0·0191	25	0·0529	17	0·0613	16	0·0595	17
25	0·0181	26	0·0222	24	0·0614	16	0·0711	15	0·0690	15
30	0·0205	25	0·0250	23	0·0694	15	0·0803	14	0·0779	14
35	0·0227	24	0·0277	22	0·0769	14	0·0890	13	0·0864	13
40	0·0248	23	8·0303	21	0·0840	14	0·0973	13	0·0944	13
45	0·0268	22	0·0328	21	0·0909	13	0·1052	12	0·1021	12
50	0·0288	22	0·0352	20	0·0975	13	0·1129	11	0·1095	12
60	0·0325	21	0·0397	19	0·1101	11	0·1275	10	0·1237	10
70	0·0360	20	0·0440	19	0·1220	10	0·1413	9	0·1371	9
80	0·0394	19	0·0481	18	0·1334	10	0·1544	8	0·1499	9
90	0·0426	19	0·0520	18	0·1443	9	0·1671	8	0·1621	8
100	0·0457	18	0·0558	17	0·1548	8	0·1792	7	0·1739	7
120	0·0516	17	0·0630	16	0·1748	7	0·2024	6	0·1964	6

APPENDIX D

TYPICAL DIAGRAMS OF CONNECTIONS

Under this heading, a number of useful diagrams are brought together for reference.

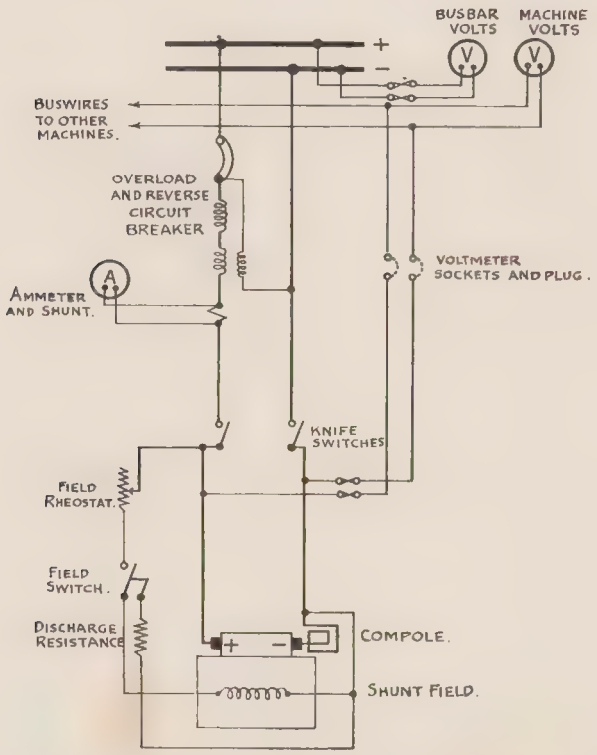


FIG. D-1.—*Two-wire shunt wound D.C. Generator.*

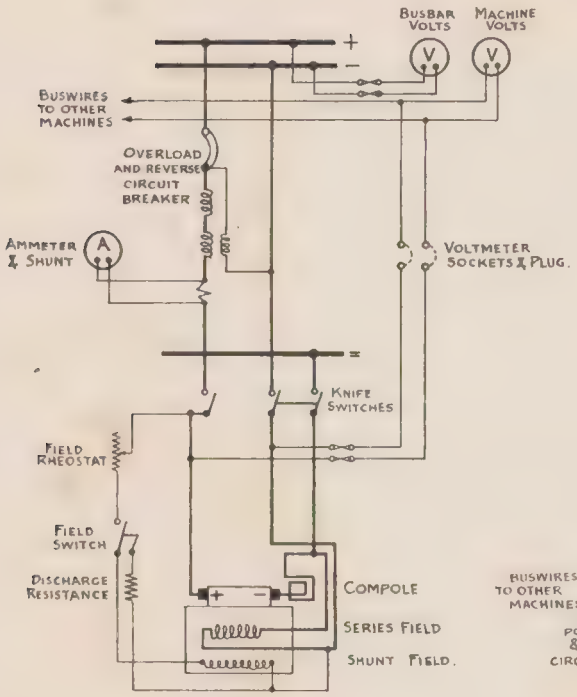


FIG. D-2.—*Two-wire compound wound D.C. Generator.*

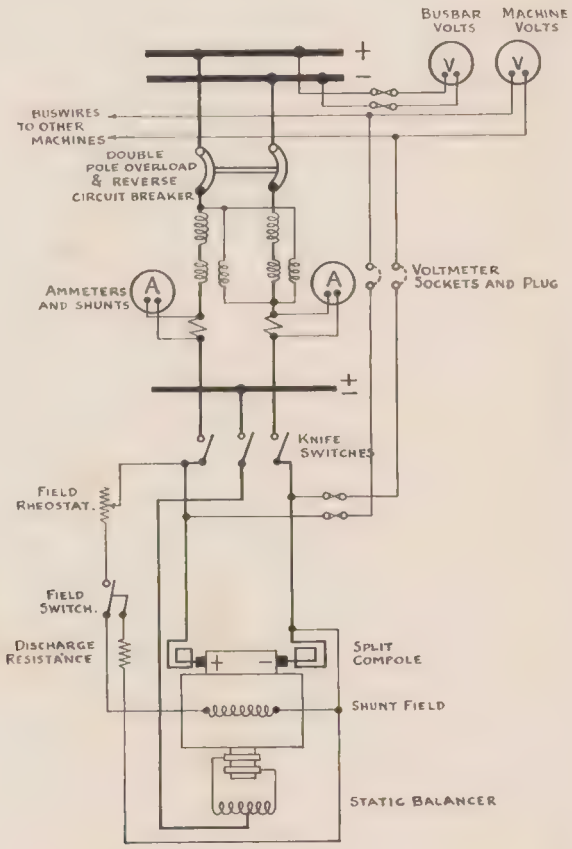


FIG. D-3.—*Three-wire shunt wound D.C. Generator.*

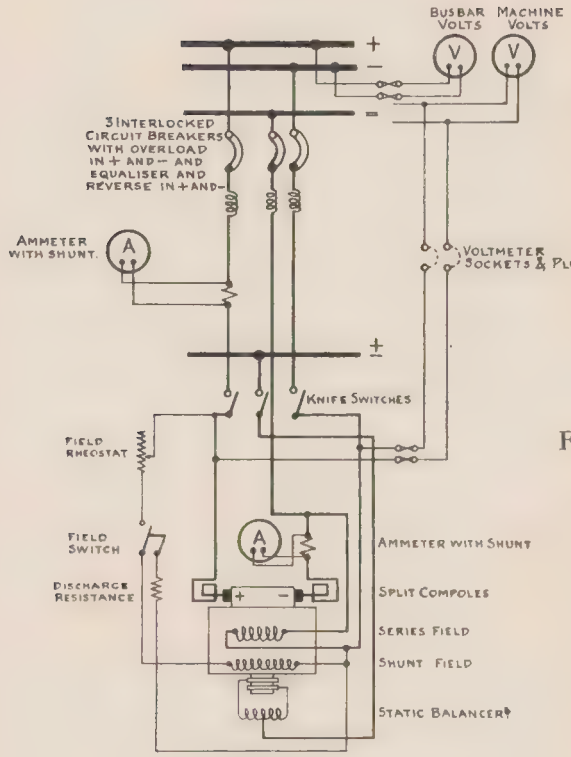


FIG. D-4.—*Three-wire compound wound D.C. Generator.*

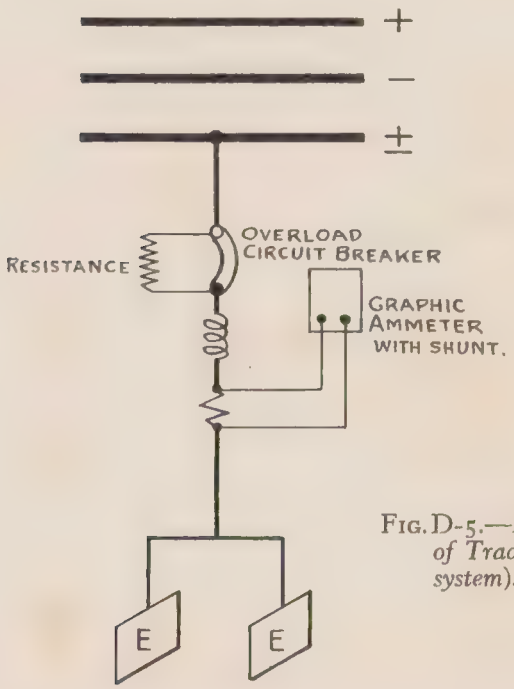


FIG. D-5.—*Diagram of Board of Trade Panel (lighting system).*

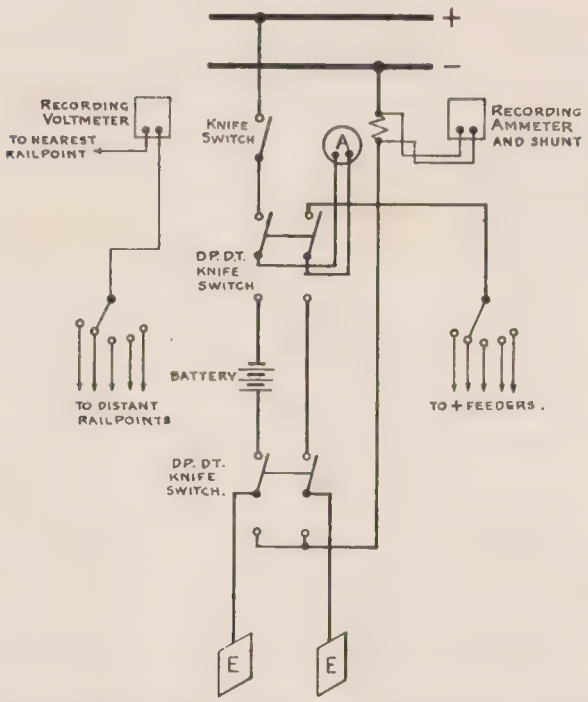


FIG. D-6.—*Diagram of Board of Trade Panel (traction system).*

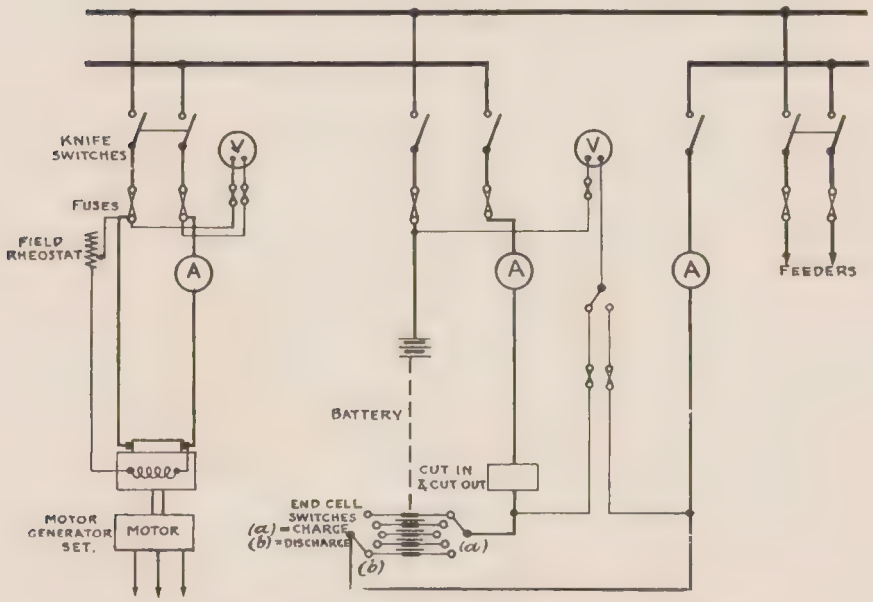


FIG. D-7.—*Diagram of connections for typical Battery Panel*

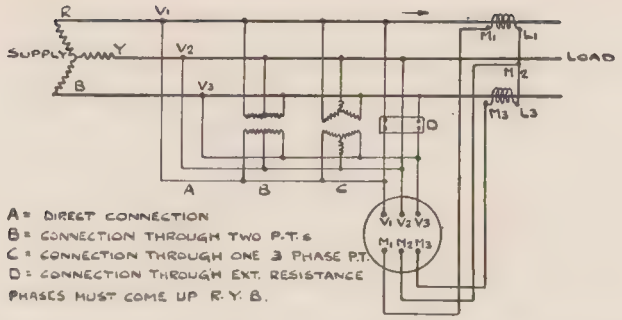


FIG. D-8.—*Connections for three-phase unbalanced load power factor Meter (Nalder Bros. & Thompson).*

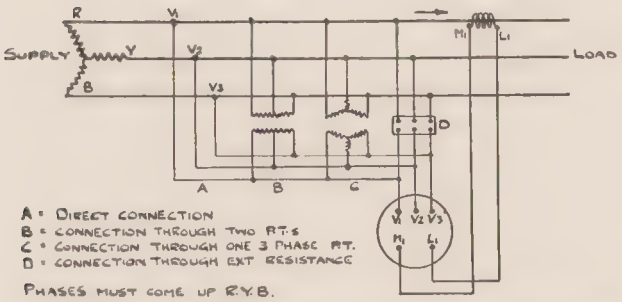


FIG. D-9.—*Connections for three-phase balanced load power factor Meter operating off one current transformer (Nalder Bros. & Thompson).*

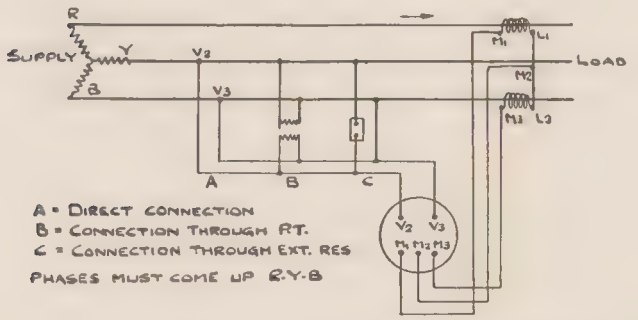


FIG. D-10.—*Connections for three-phase balanced load power factor Meter operating off two or three current transformers (Nalder Bros. & Thompson).*

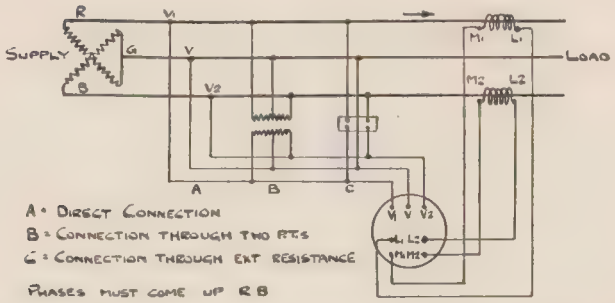


FIG D-11.—*Connections for two-phase three-wire unbalanced load power factor Meter (Nalder Bros. & Thompson).*

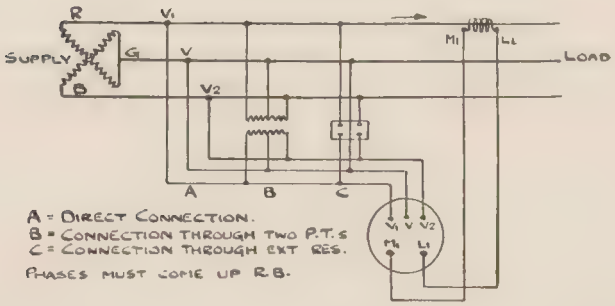


FIG. D-12.—*Connections for two-phase three-wire balanced load power factor Meter (Nalder Bros. & Thompson).*

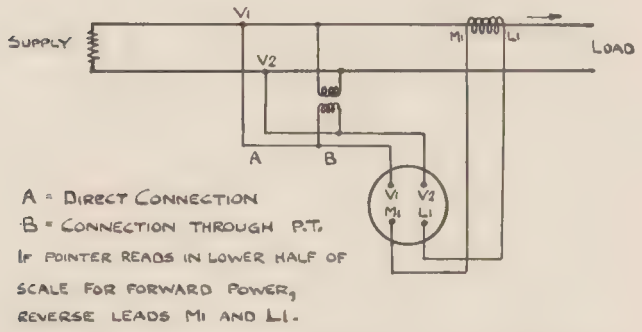


FIG. D-13.—*Connections for single-phase power factor Meter (Nalder Bros. & Thompson).*

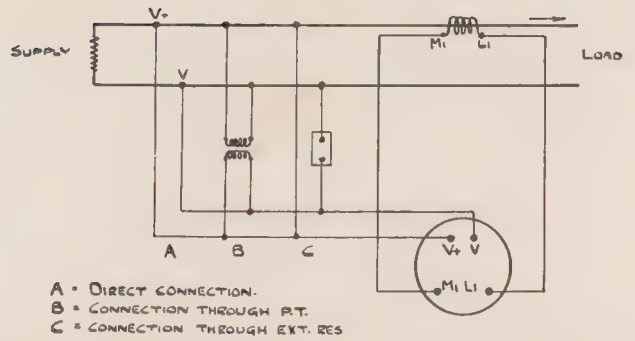


FIG. D-14.—*Connections for single-phase indicating Wattmeter (Nalder Bros. & Thompson).*

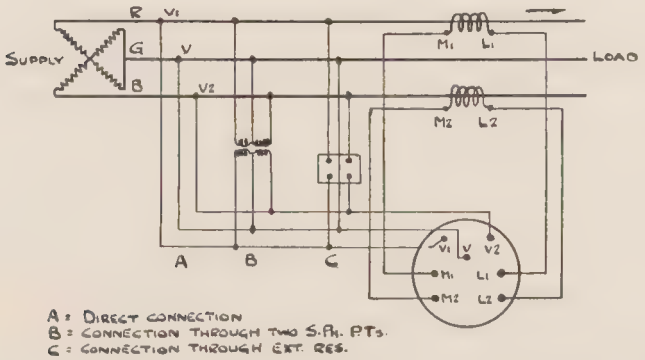


FIG. D-15.—*Connections for two-phase three-wire unbalanced load indicating Wattmeter (Nalder Bros. & Thompson).*

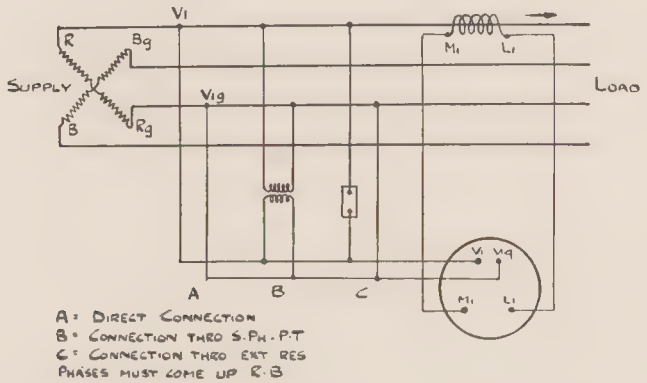


FIG. D-16.—*Connections for two-phase four-wire balanced load indicating Wattmeter (Nalder Bros. & Thompson).*

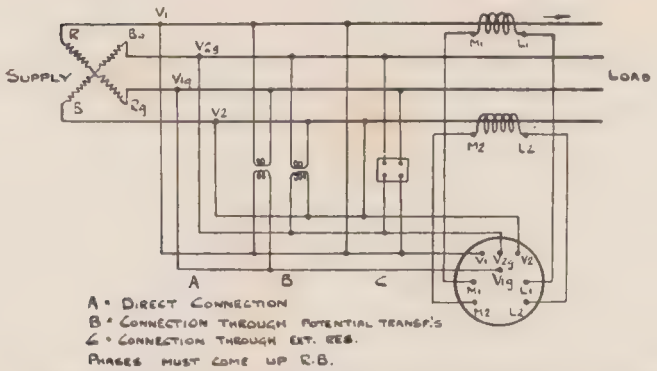


FIG. D-17.—*Connections for two-phase four-wire unbalanced load indicating Wattmeter (Nalder Bros. & Thompson).*

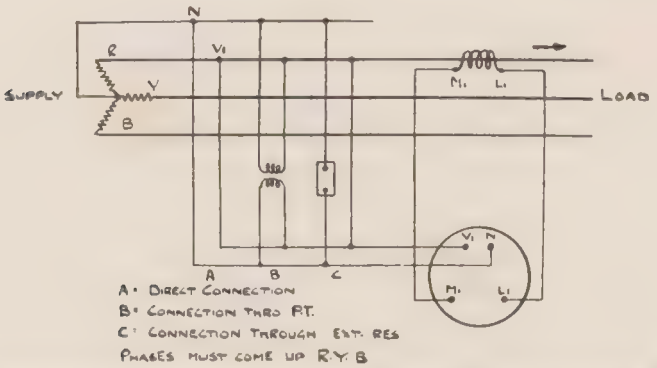


FIG. D-18.—*Connections for three-phase balanced load indicating Wattmeter —neutral point available (Nalder Bros. & Thompson).*

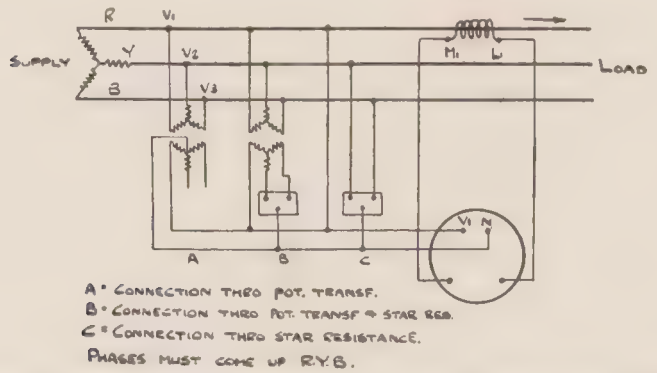


FIG. D-19.—*Connections for three-phase balanced load indicating Wattmeter —neutral point not available (Nalder Bros. & Thompson).*

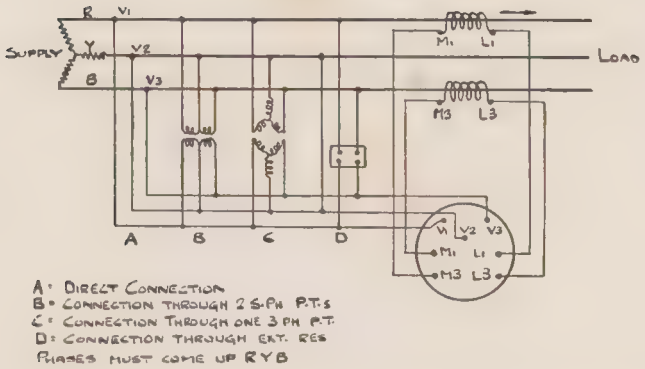


FIG. D-20.—*Connections for three-phase three-wire unbalanced load indicating Wattmeter (Nalder Bros. & Thompson).*

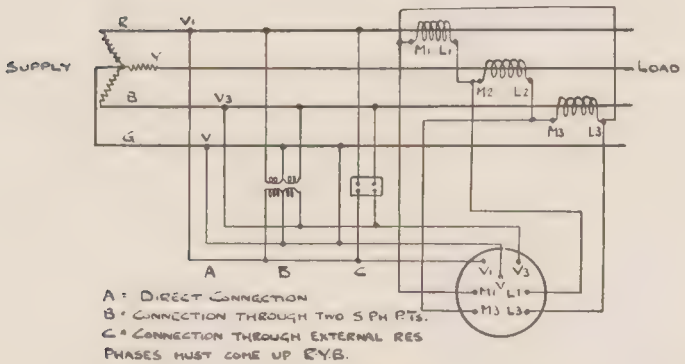
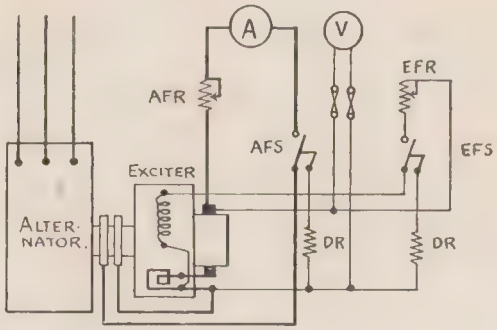


FIG. D-21.—*Connections for three-phase four-wire unbalanced load indicating Wattmeter (Nalder Bros. & Thompson).*

NOTE.—ONLY ONE FIELD SWITCH IS NECESSARY EITHER IN THE EXCITER OR MAIN FIELD.

THE DISCHARGE RESISTANCE IN THE MAIN FIELD MAY BE DISPENSED WITH FOR CERTAIN DESIGNS OF ALTERNATOR.

THE RHEOSTAT IN THE MAIN FIELD IS OPTIONAL.



A — AMMETER.
V — VOLTMETER.
AFR — ALTERNATOR FIELD RHEOSTAT.
EFR — EXCITER " "
AFS — ALTERNATOR FIELD SWITCH.
EFS — EXCITER " "
DR — DISCHARGE RESISTANCES.

FIG. D-23.—*Simplified Key to alternator field equipment.*

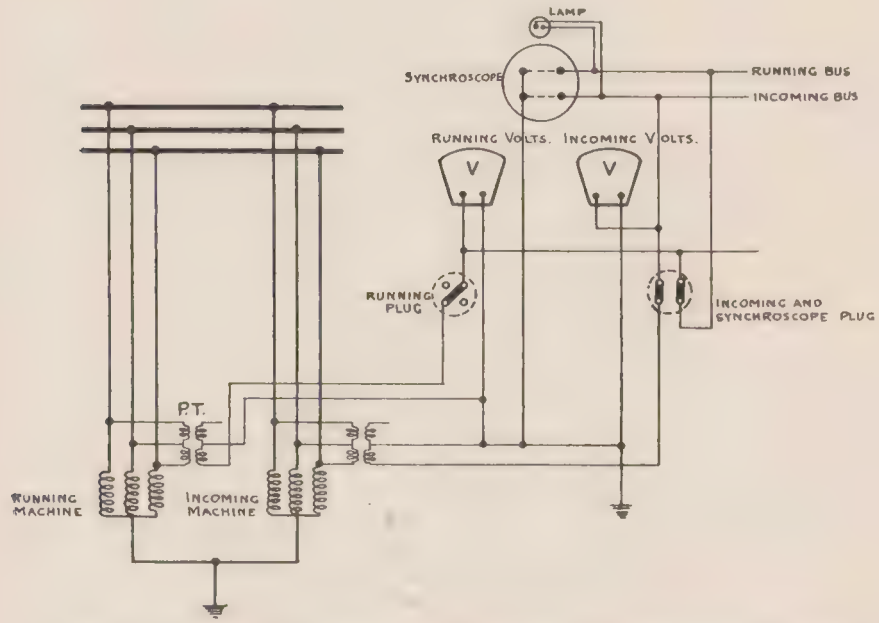


FIG. D-24.—*Typical Synchronising Connections —synchronising between machines and Lamp Dark at synchronism.*

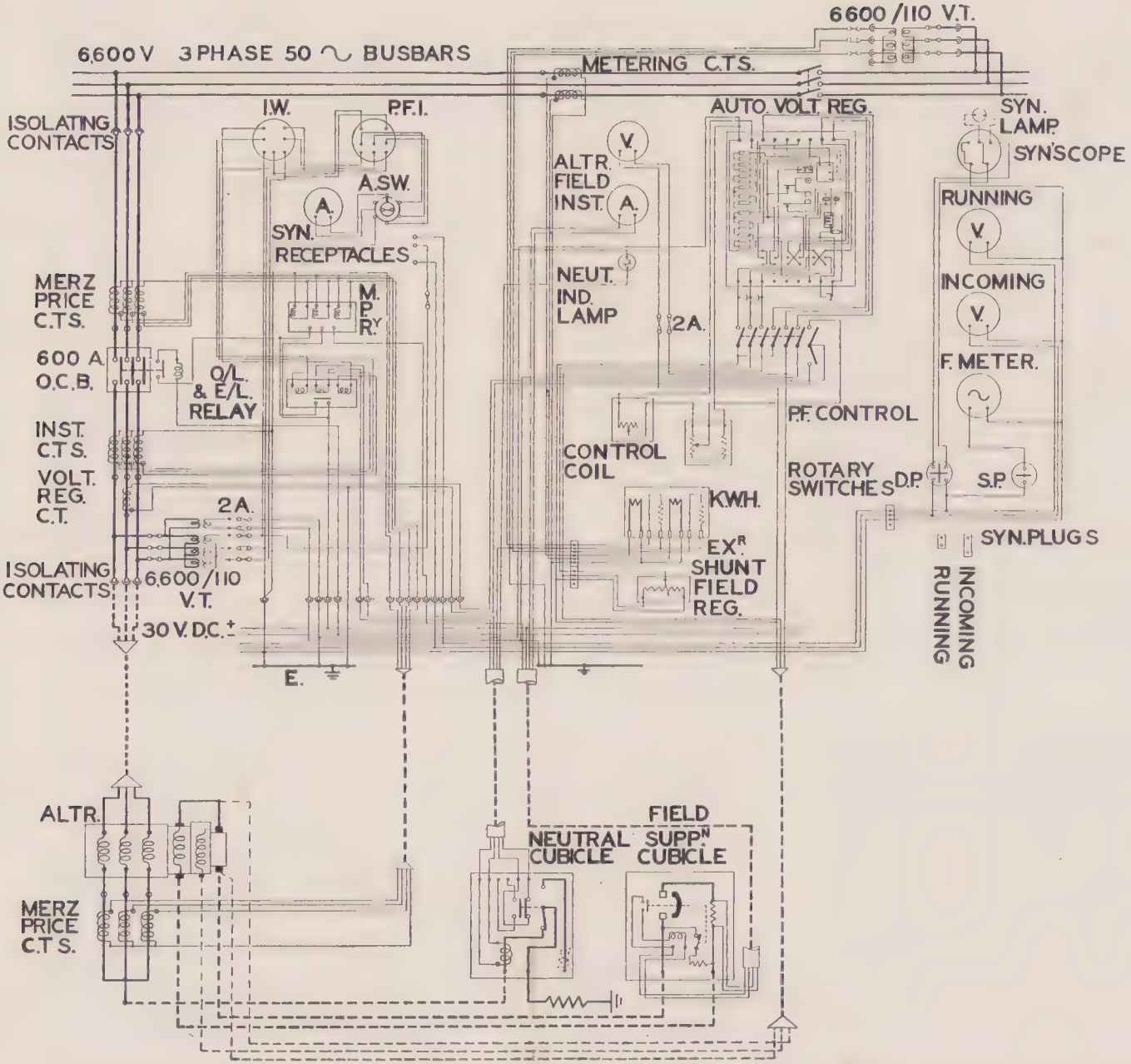


FIG. D-22.—*Typical Connection Diagram for small alternator with Metering, Voltage Regulator, Synchronising and Field Equipment.*

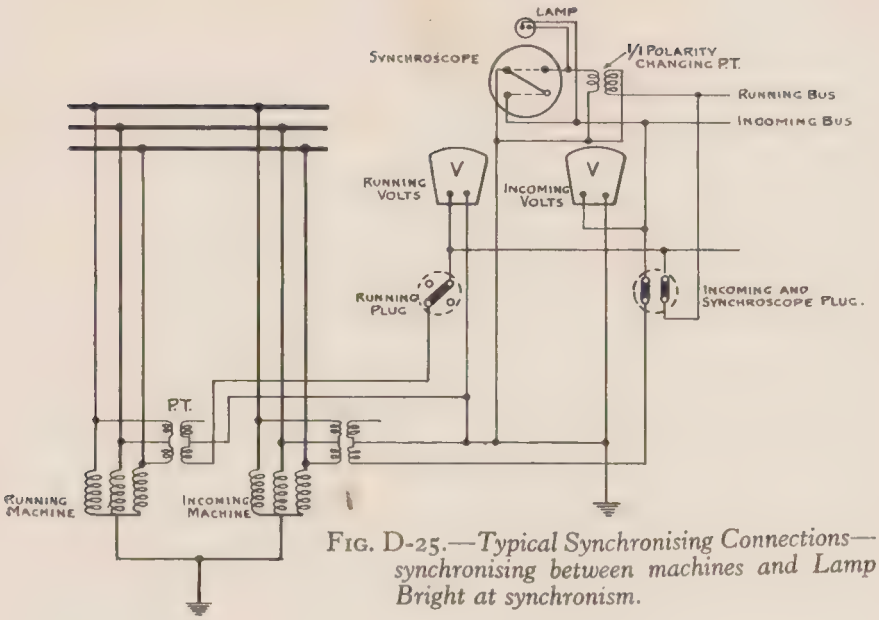


FIG. D-25.—*Typical Synchronising Connections—synchronising between machines and Lamp Bright at synchronism.*

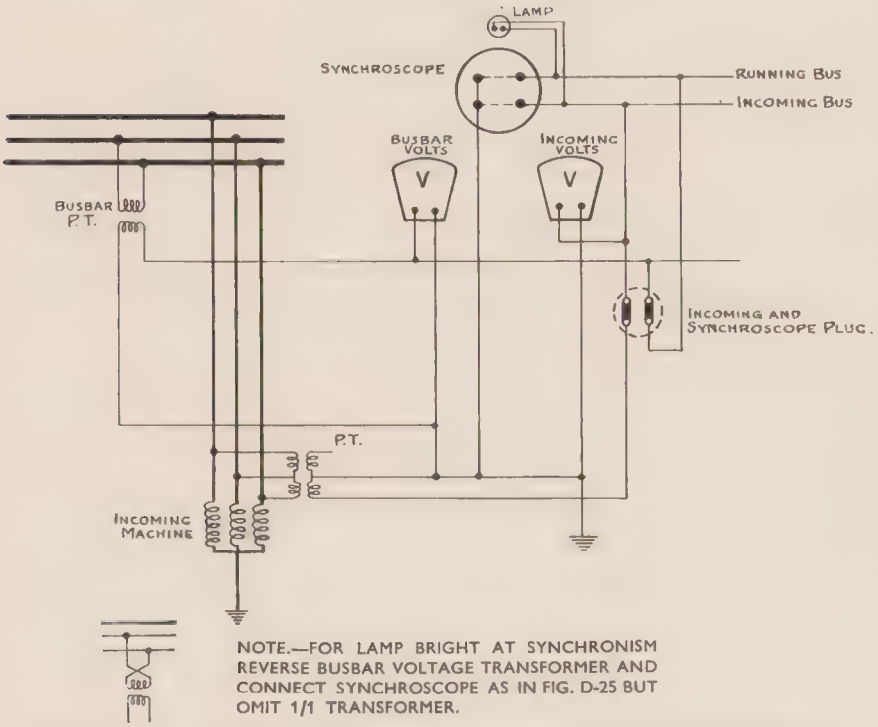


FIG. D-26.—*Typical Synchronising Connections—synchronising between busbars and machines and Lamp Dark at synchronism.*

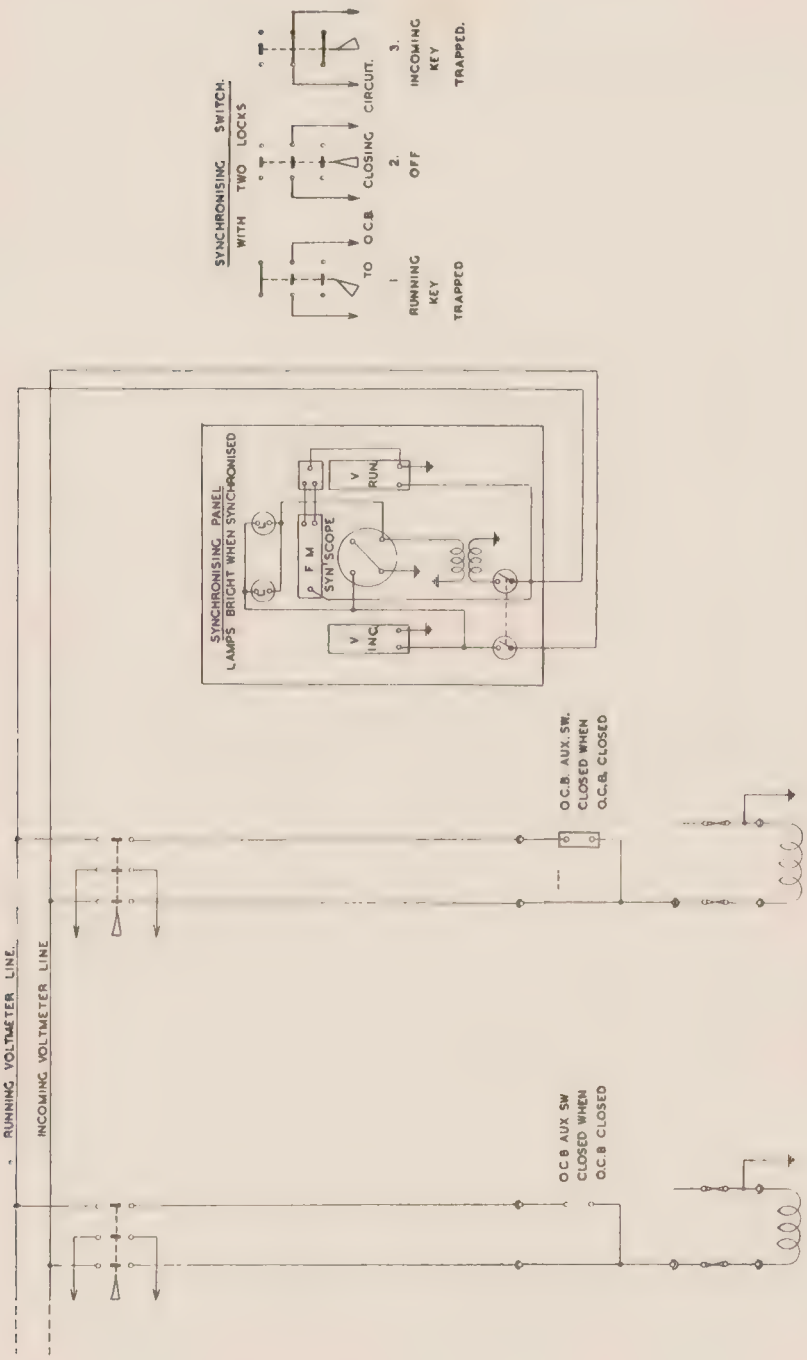


FIG. D-27.—*Synchronising Scheme using key interlocked control switches.*

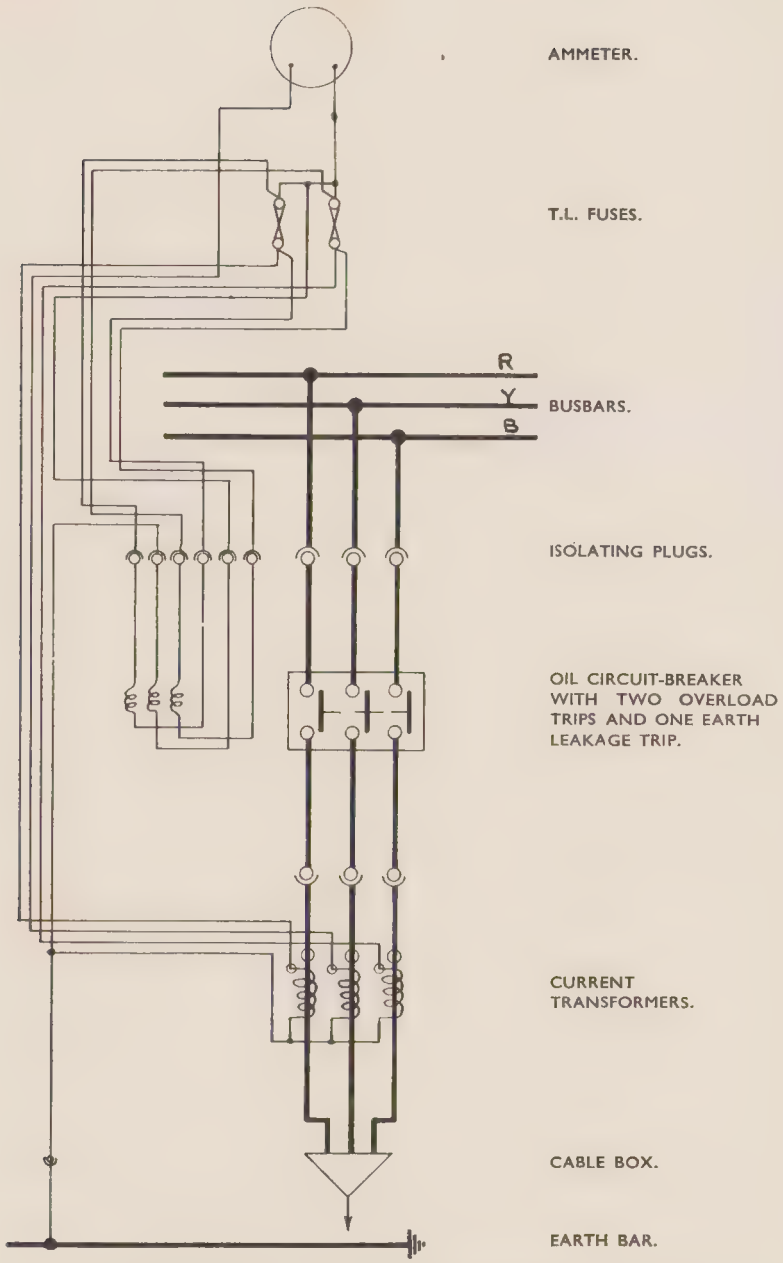


FIG. D-28.—*Simple Transformer Feeder with time limit Fused Overloads and Instantaneous Earth Leakage.*

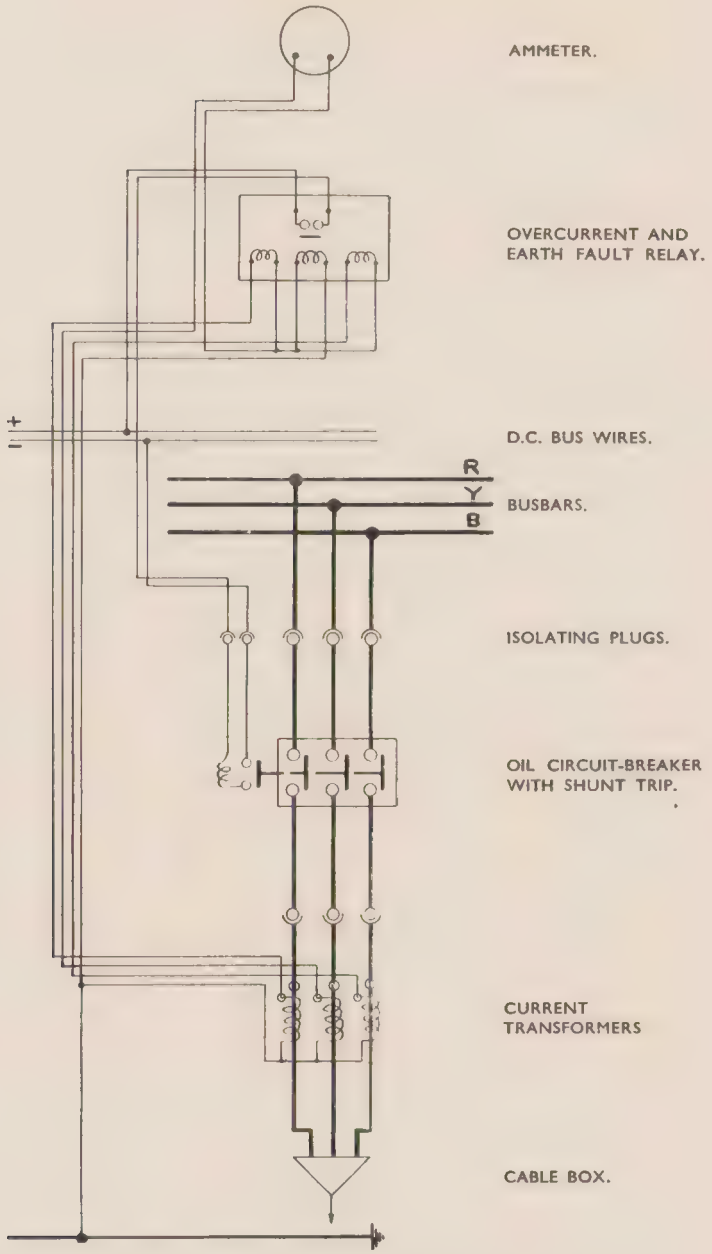


FIG. D-29.—*Simple Feeder or Transformer with overcurrent and earth fault relay.*

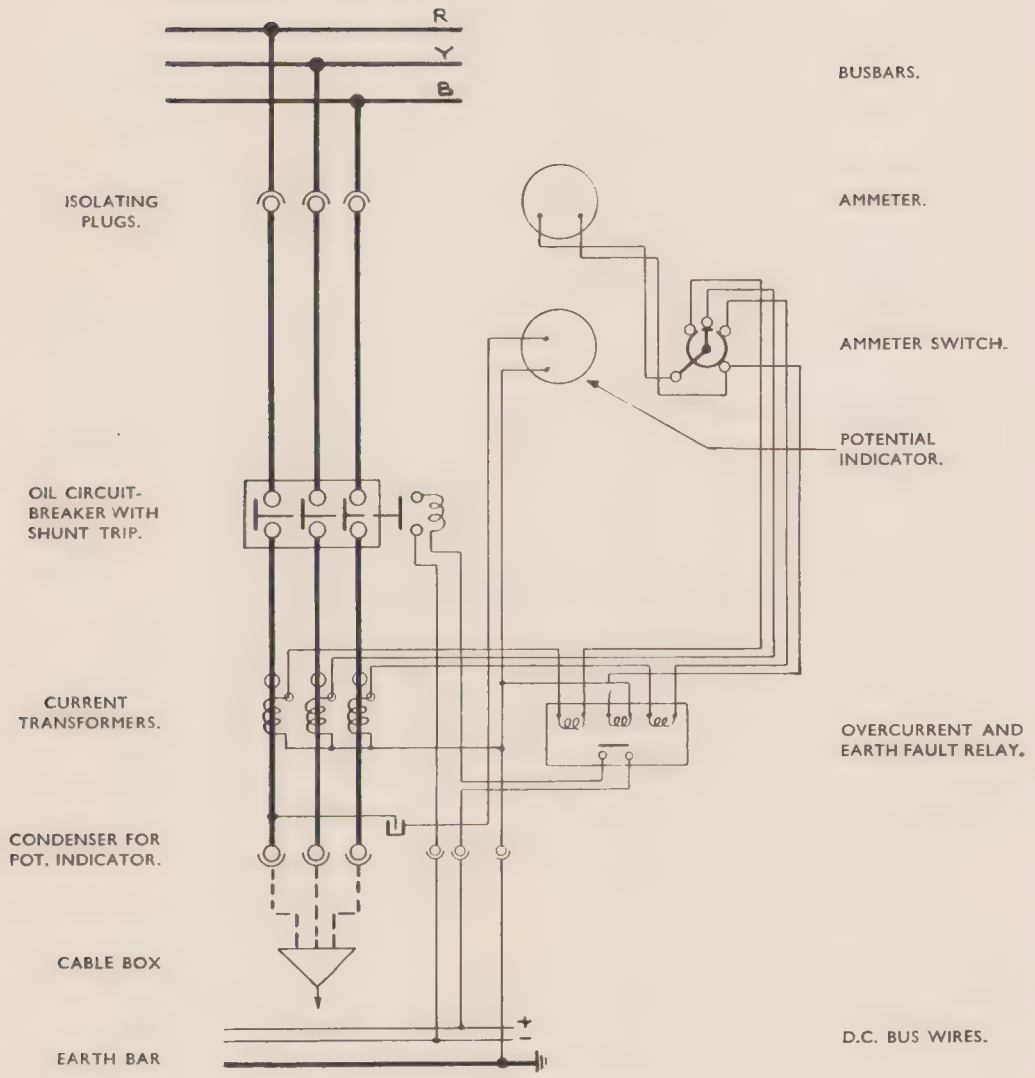


FIG. D-30.—*Simple Feeder with overcurrent and earth fault relay, Ammeter with three-way switch, and Neon Potential Indicator operated from condenser bushing.*

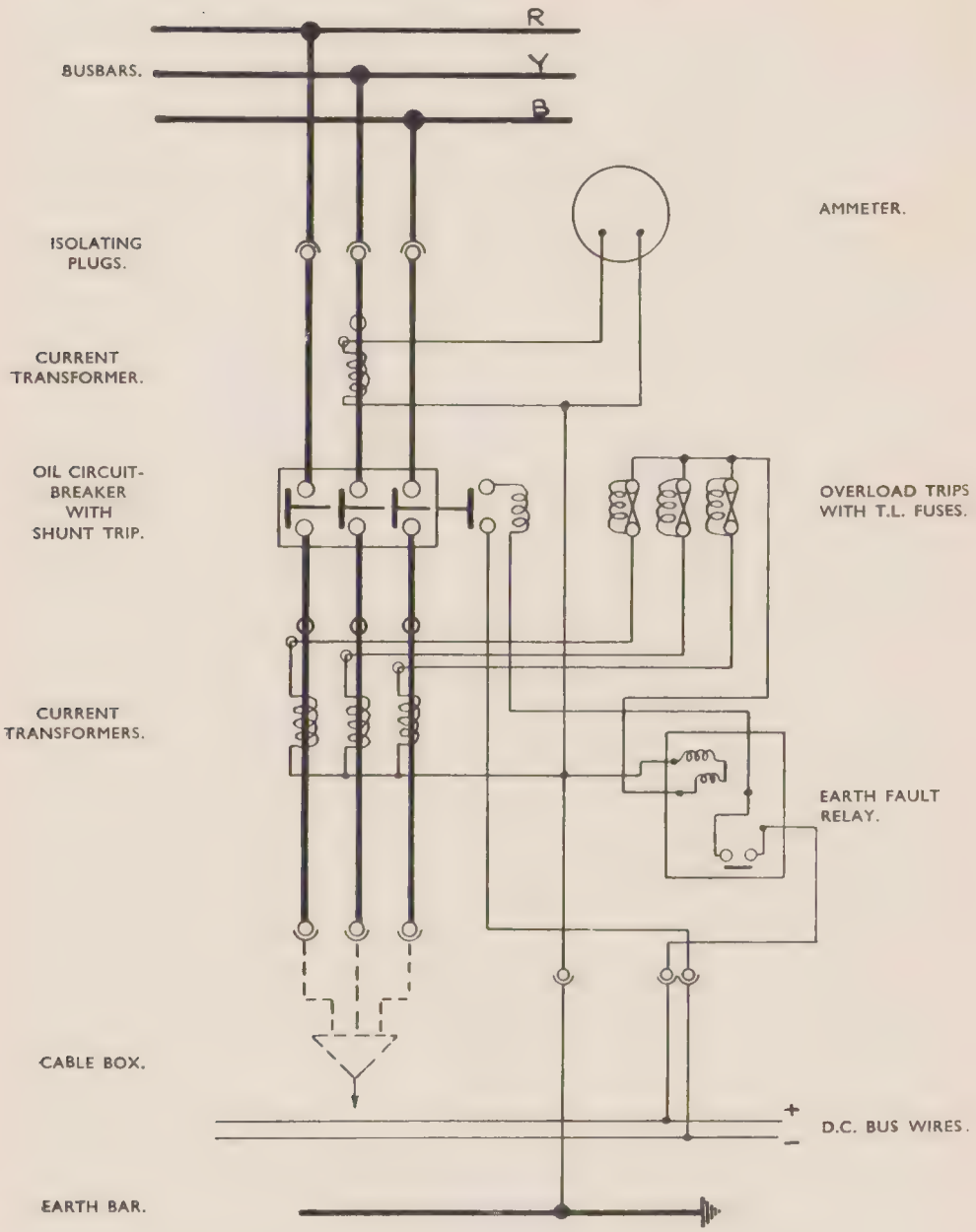


FIG. D-31.—*Simple Feeder with fused overloads and separate earth fault relay.*

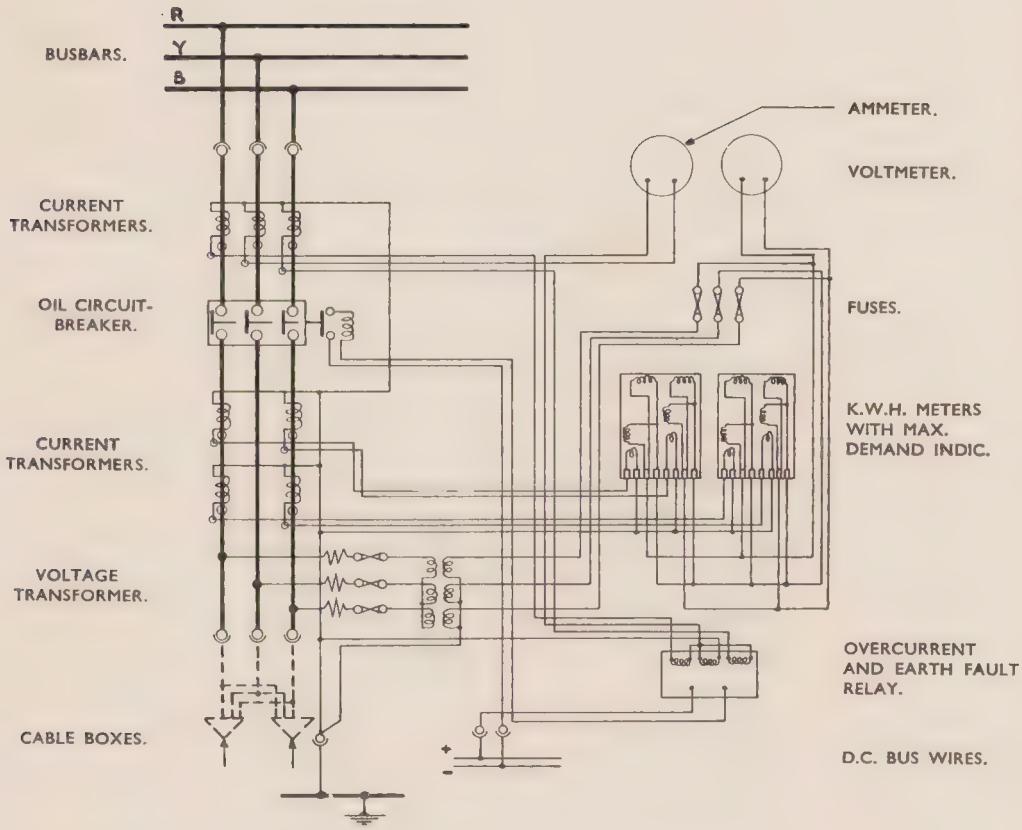


FIG. D-32.—*Bulk Supply Incoming Feeder with overcurrent and earth fault relay protection, duplicate metering equipment.*

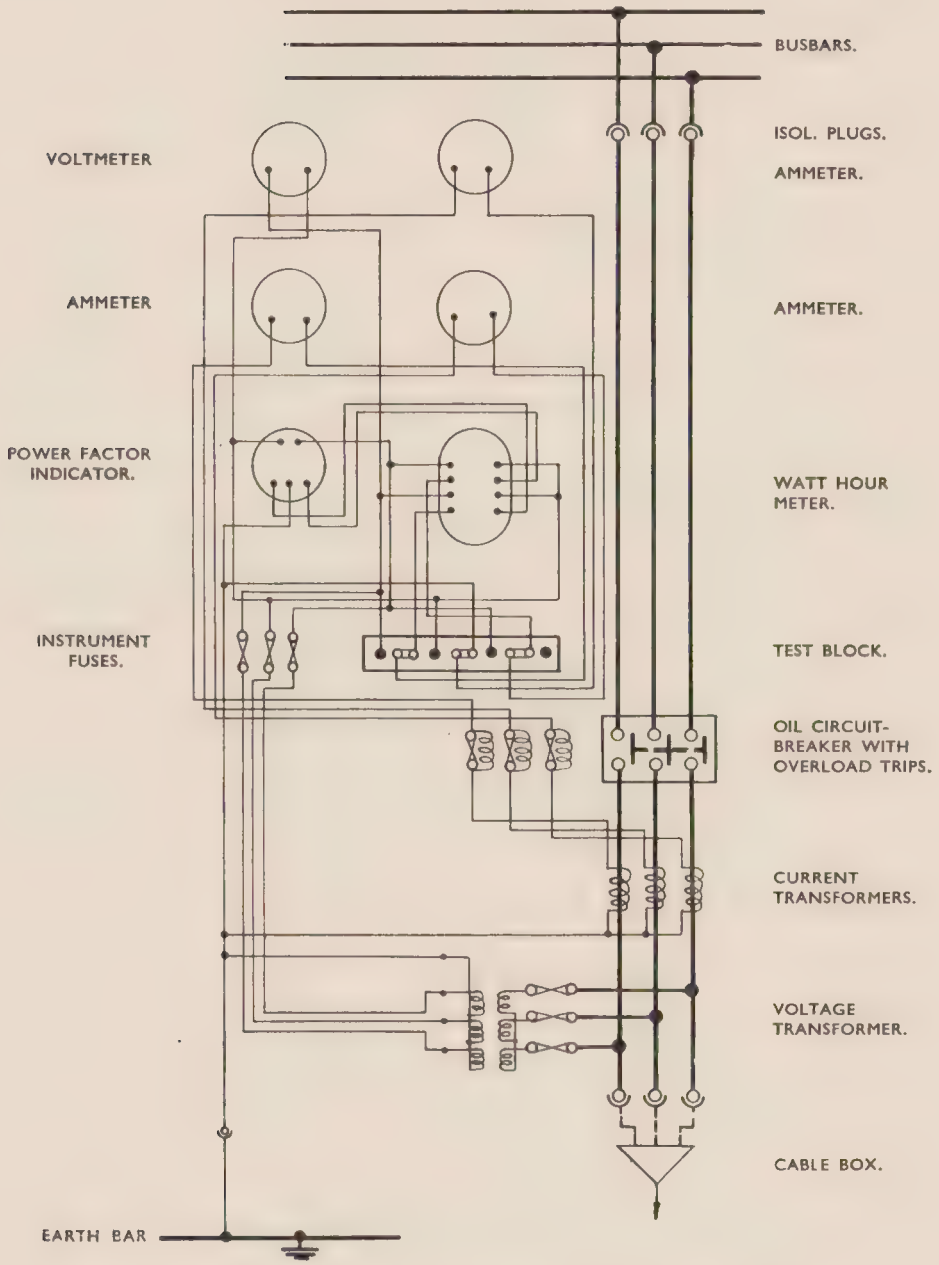


FIG. D-33.—*Simple Transformer Feeder with metering and test block, and fused overloads.*

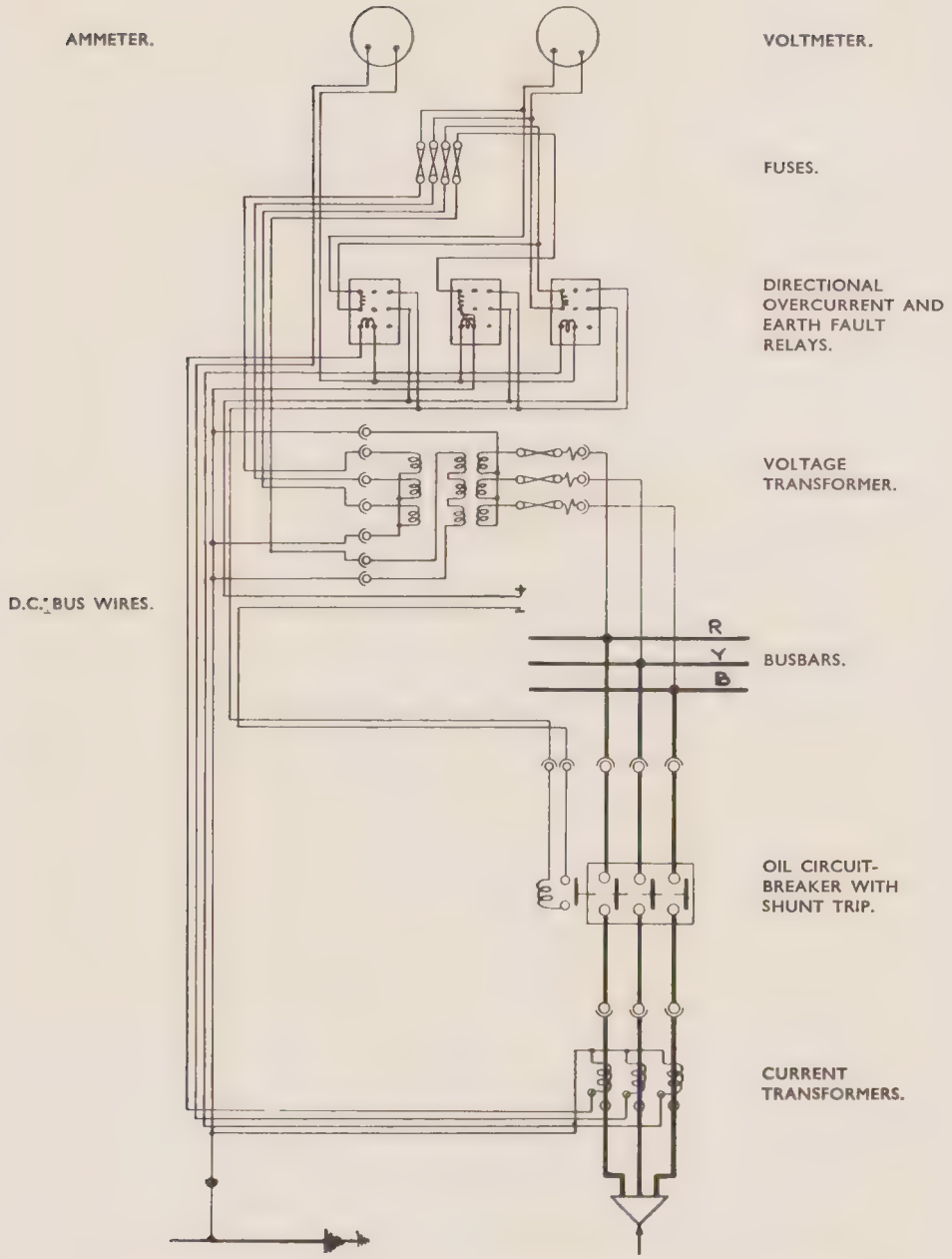


FIG. D-34.—*Feeder with directional overcurrent and earth fault relay protection. Voltage transformer has Delta connected Tertiary winding for voltage element of earth fault relay (see Chapter XVIII).*

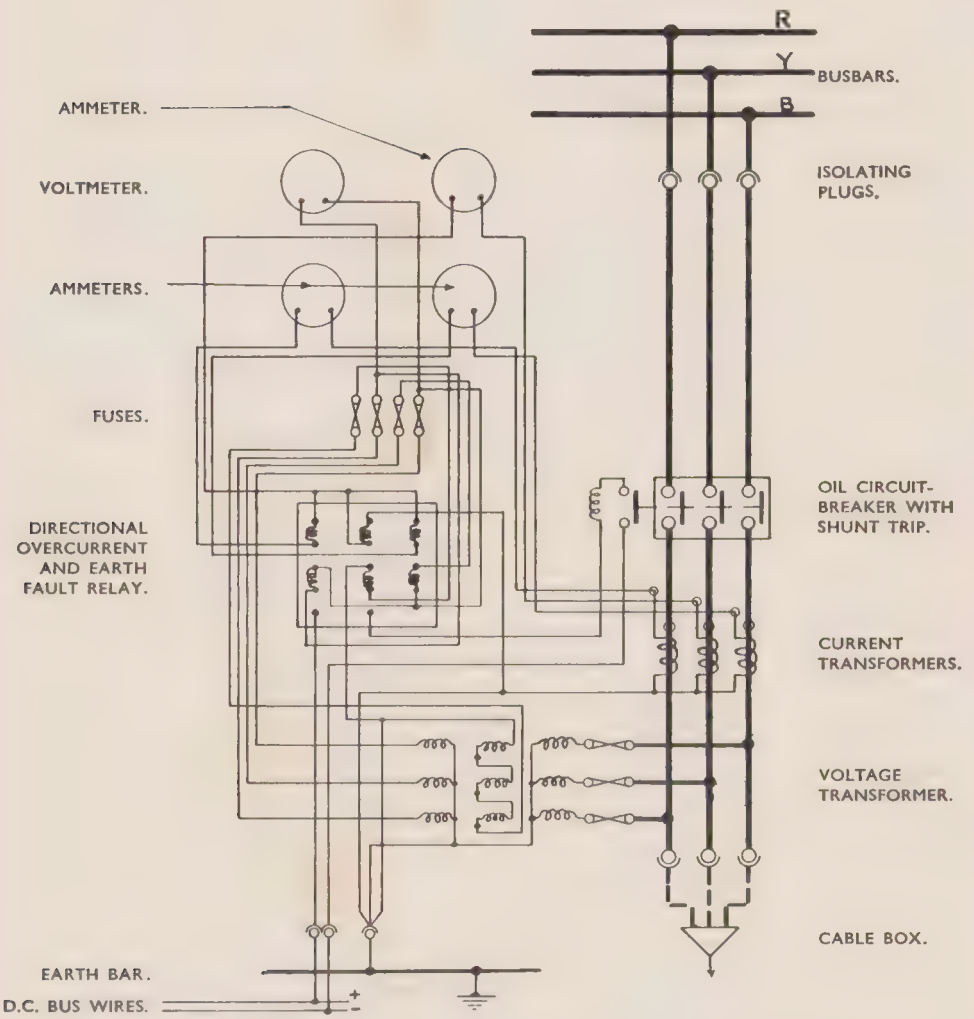


FIG. D-35.—*Feeder with directional overcurrent and earth fault relay protection similar to Fig. D-34 but with three-pole relay.*

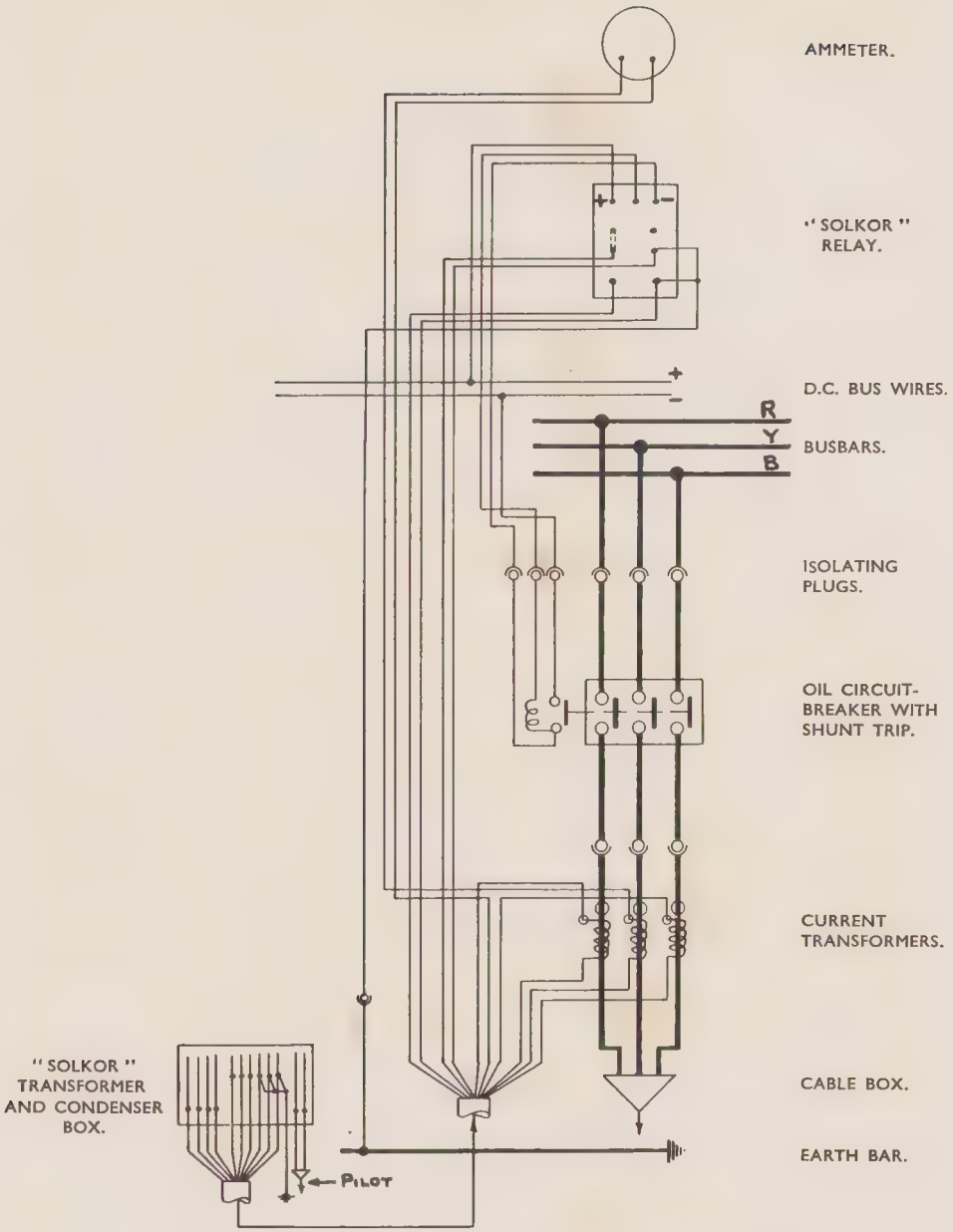


FIG. D-36.—*Feeder with "Solkor" (Reyrolle) protection*

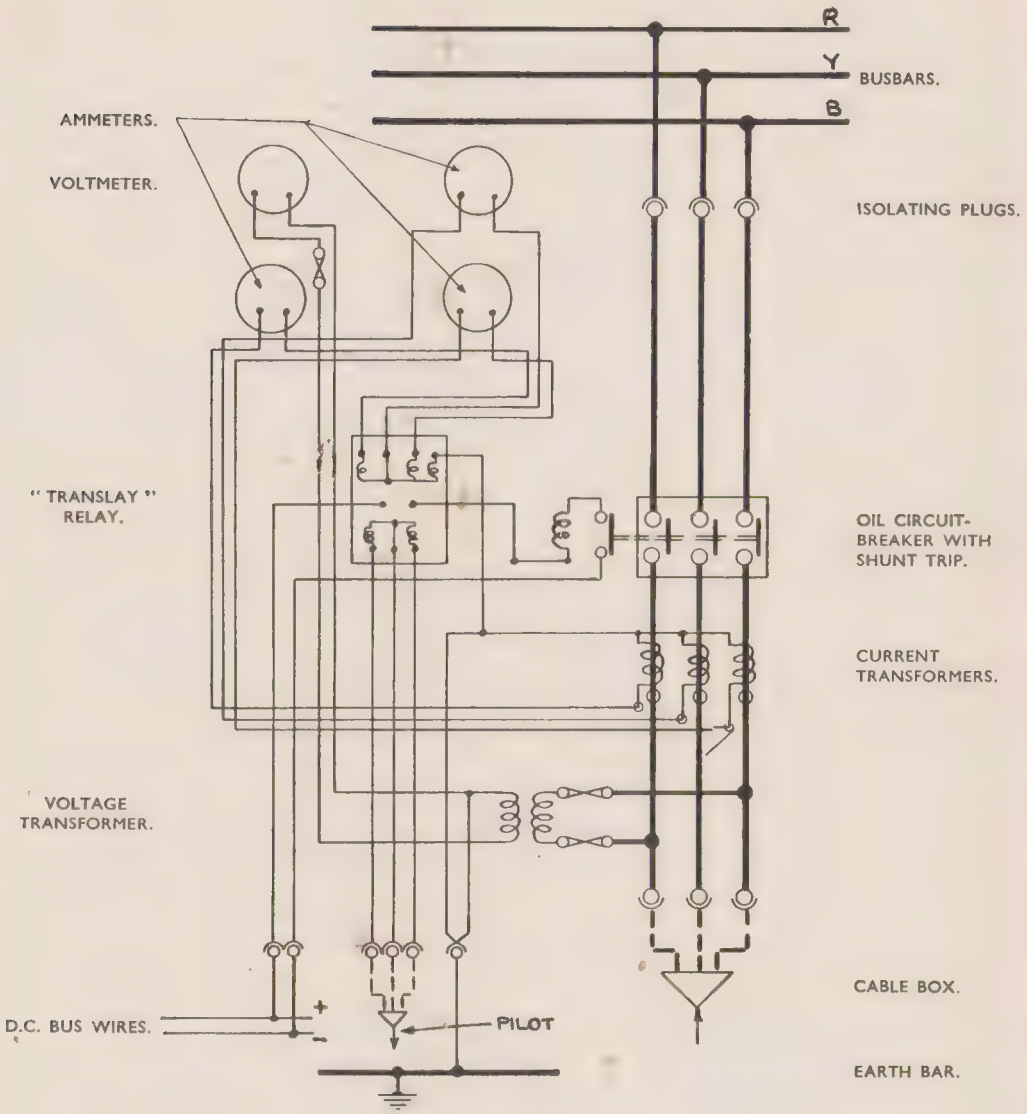


FIG. D-37.—*Feeder with " Translay " (The Metropolitan-Vickers Electrical Co., Ltd.) protection.*

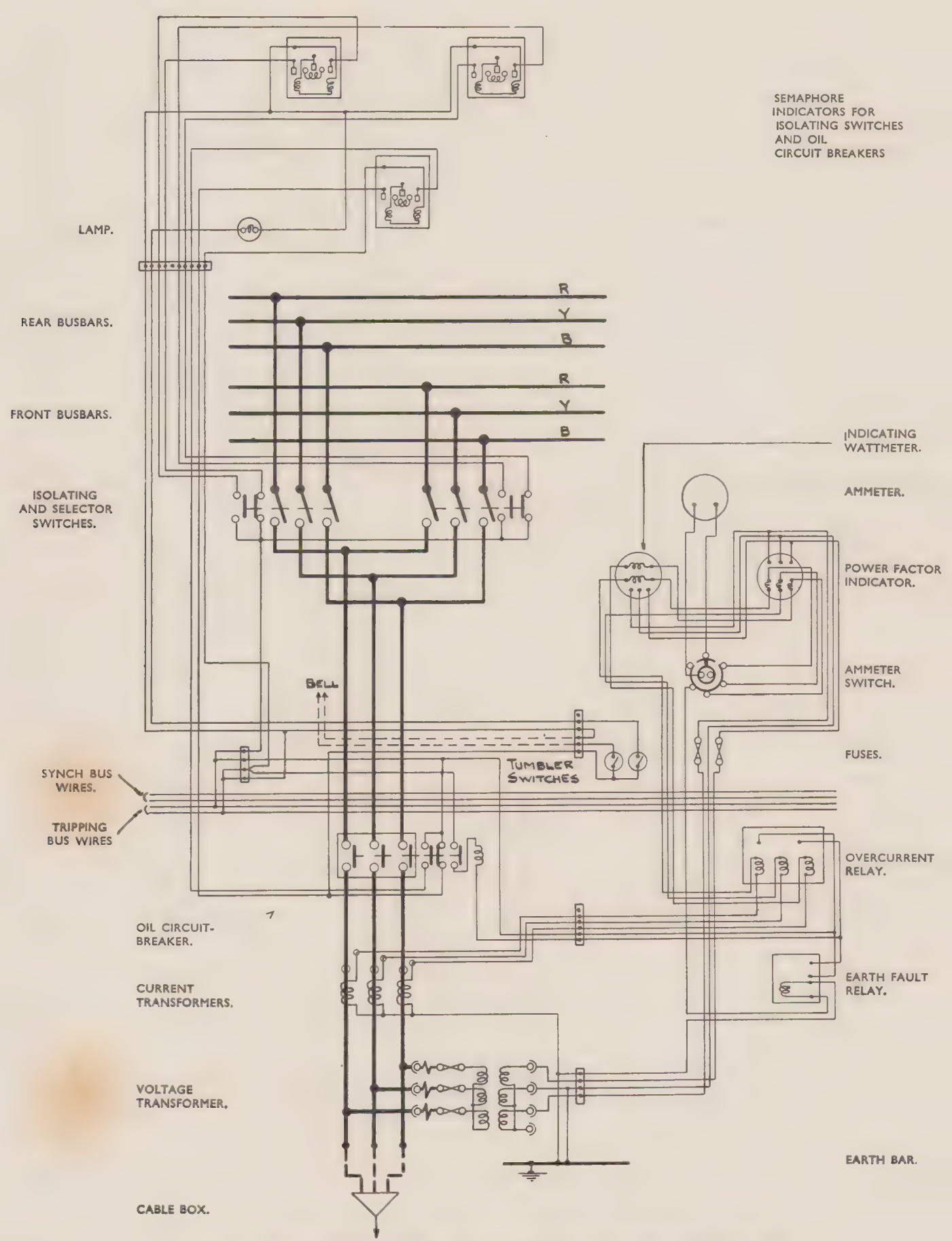


FIG. D-38.—*Outgoing Feeder, Duplicate Busbars, with mimic diagram using semaphore indicators. Overcurrent and earth fault relays.*

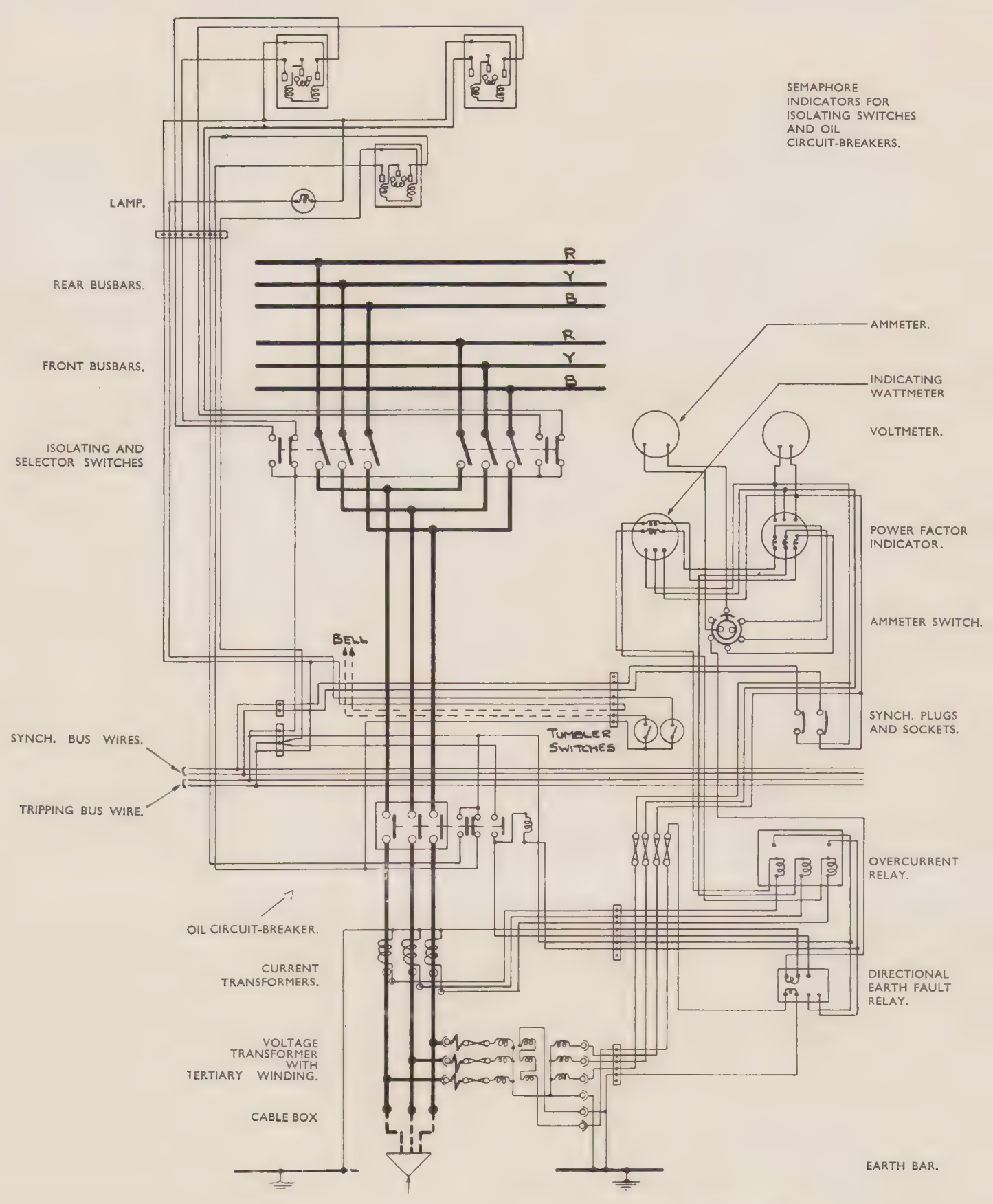


FIG. D-39.—*Incoming Feeder, Duplicate Busbars, with mimic diagram using semaphore indicators. Earth fault relay is of directional type.*

BRITISH STANDARD SPECIFICATIONS

THE following is a list of Specifications issued by The British Standards Institution which relate to electrical switchgear or ancillary apparatus as described in this volume. The year of issue has not been stated as this dates the Specification when revisions are made. The current issue is assumed.

B.S. No.	*Title (abbreviated).*
81	Instrument Transformers.
88	Electric Fuses.
89	Indicating Instruments.
90	Graphic (Recording) Instruments.
108	Graphical Symbols.
116	Oil Circuit-Breakers.
142	Protective Relays.
148	Insulating Oils.
158	Marking and Arrangement of Busbars and Connections.
159	Busbars and Connections.
160	Slate and Marble Panels.
162	Electrical Power Switchgear.
194	Switchgear Equipment for d.c. circuits up to 660 V.
195	Switchgear Equipment for 3-phase a.c. circuits up to 33 kV.
223	H.V. Bushing Insulators.
229	Flameproof Enclosures.
268	Concrete or Moulded Stone Cells.
688	Compounds for Electrical Apparatus.
803	Compounds for Cable Boxes up to and including 11 kV
861	Air-break Switches up to 660 V.
862	Air-break Circuit-Breakers up to 660 V.
923	Impulse Testing.
936	Oil Circuit-Breakers up to 1,000 V.
1086	Maintenance of Electrical Switchgear.

ACKNOWLEDGMENTS

In the preparation of this work, the Author has received ready and valuable assistance from a number of sources, particularly from manufacturers. They have freely contributed considerable material concerning designs and data, which has enabled the Author to present an outline of practice which covers a wide range not necessarily that of one maker. In addition, The Institution of Electrical Engineers and Sir Isaac Pitman and Sons Ltd. have readily granted permission to use certain material and illustrations, the former from the Journal of the Institution in respect to a paper by the Author, and the latter from the book " Calculation of Fault Currents in Electrical Networks," also by the Author and published by them.

For this assistance, and to those who, as mentioned in the Preface, have specially contributed, grateful acknowledgment is made, noting also that illustrations and data are further acknowledged by giving reference to their source at the actual point of use.

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Quotations from British Standard Specifications are noted in the text and acknowledgment to the British Standards Institution is hereby made.

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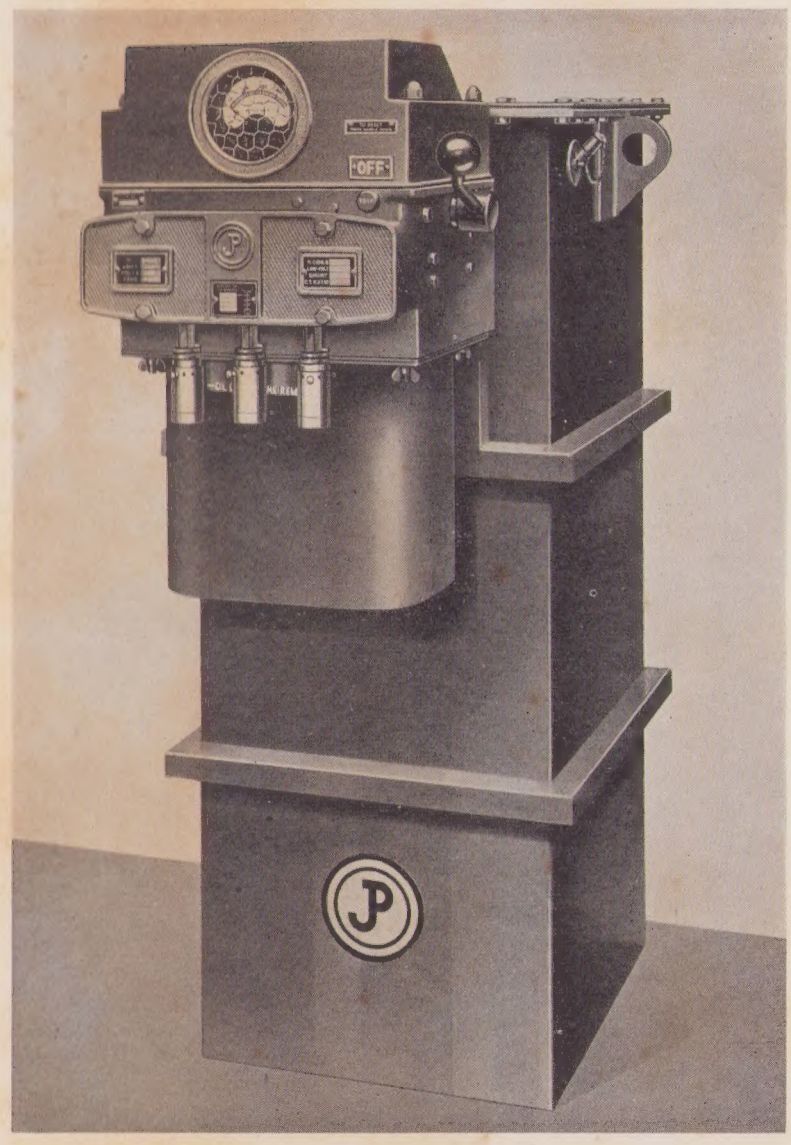
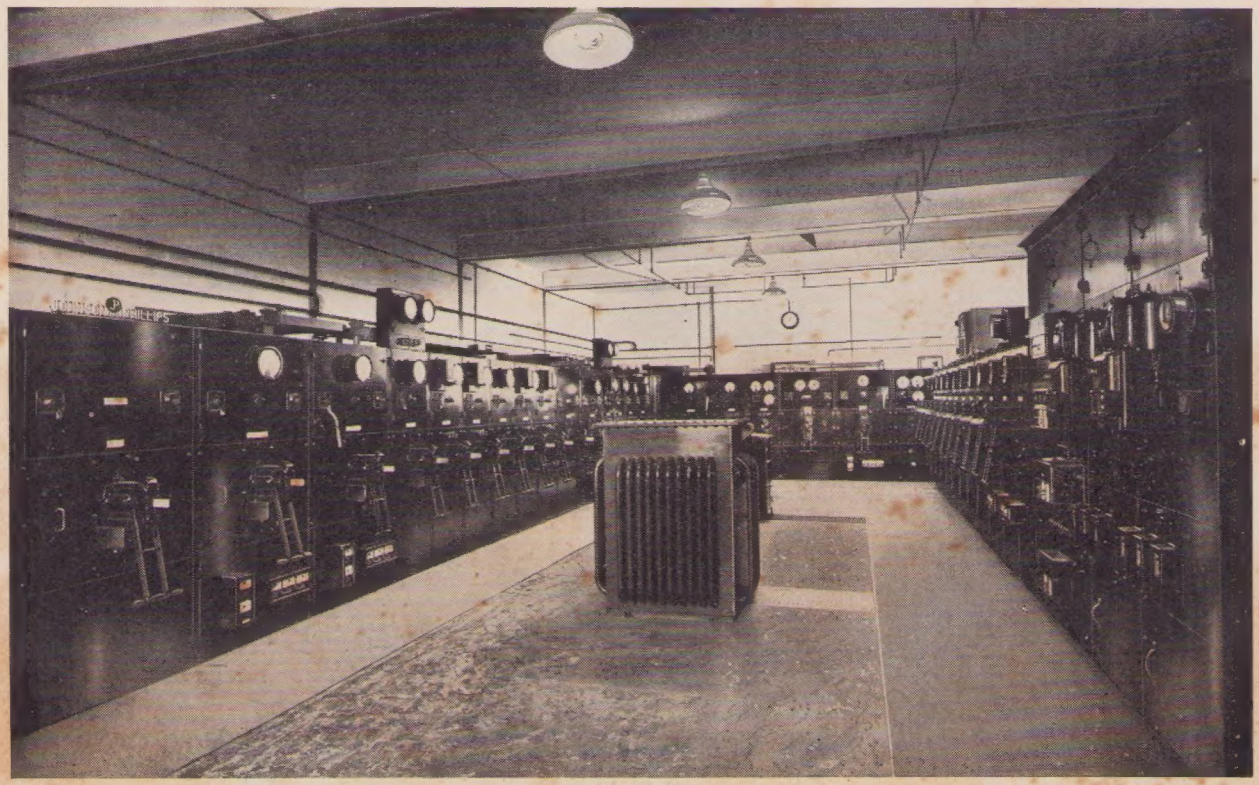
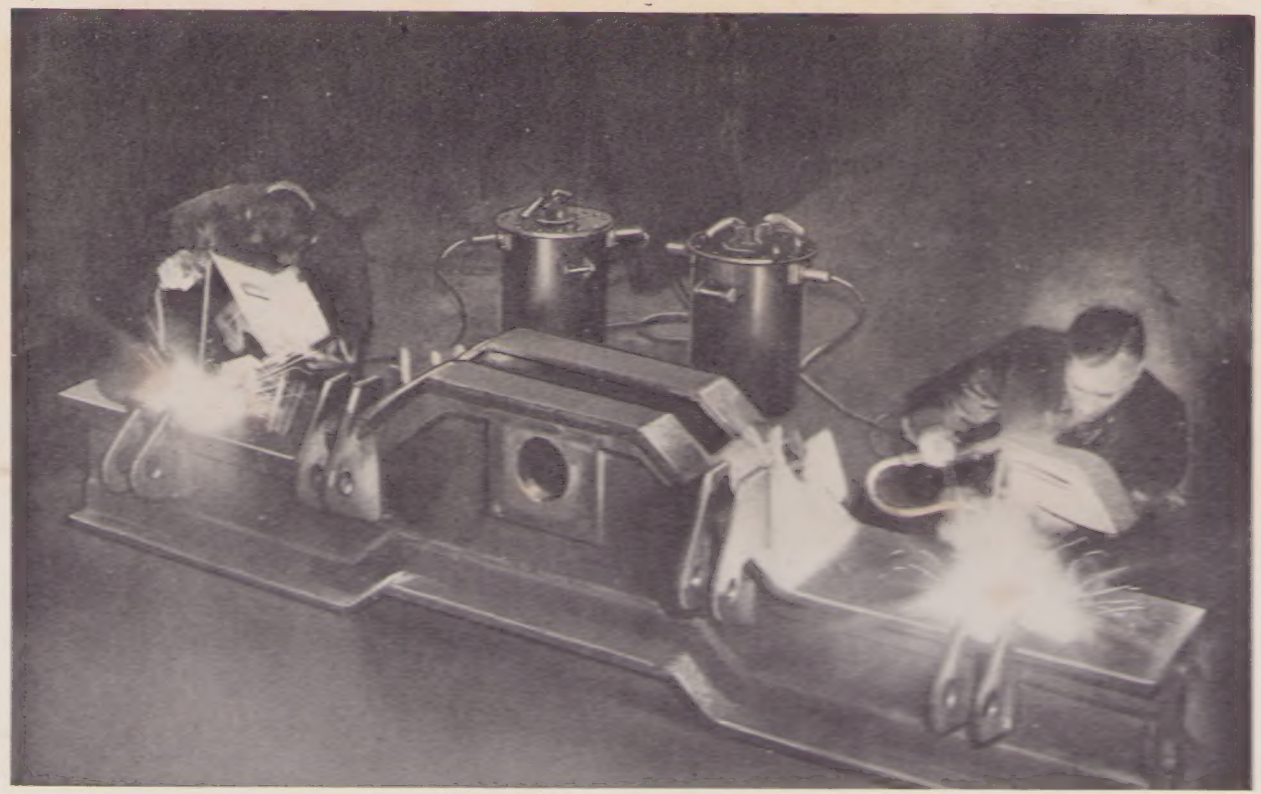


The installation of a 110kVAr J. & P. Capacitor similar to that illustrated can effect a saving of £150—£250 per annum, according to the type of Power Factor Tariff under which power is purchased.



Sub-station for the Redditch factory of High Duty Alloys Ltd. Complete factory electrification scheme undertaken by J. & P. Ltd. Ten 1,000 kVA J. & P. Transformers are installed in fire-proof chambers outside the building.



J. & P. Multi-operator Welding Equipment being used in the construction of an all-welded lifting beam designed to take a load of 50 tons.